Flexible hollow optical fiber bundle for infrared thermal imaging

Yuji Matsuura* and Keisuke Naito

Graduate School of Biomedical Engineering, Tohoku University, 6-6-05 Aoba, Sendai 980-8579, Japan

*yuji@ecei.tohoku.ac.jp

Abstract: A flexible and coherent bundle of hollow optical fibers was fabricated for infrared thermal imaging. For acquisition of thermal images, differences in the transmission efficiency among the fibers were numerically compensated to obtain high temperature resolution of 1°C for measuring body temperature. In a lens system with 10-fold magnification and hollow fibers of 320-μm inner diameter, the spatial resolution is around 3 mm. The hollow-fiber bundle enables observation of the surface temperature of inner organs and blood flow of the surfaces when the bundle is introduced into the human body with an endoscope.

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References and links

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1. Introduction

Thermographic cameras visualize infrared radiation that is dependent on a target’s surface temperature and its infrared emissivity. Medical diagnoses using these cameras to detect relative patterns of blood flow have been rapidly gaining popularity since they are non-invasive and do not need a complicated system [1]. Thermographic diagnoses are useful for detecting and clinically following up circulatory defects, neuromuscular abnormalities, and metabolic disorders. Recently, a combination of an ultra-sensitive thermal imaging camera and a signal processing system has been shown to enable early detection of breast cancer [2]. A thermal image is obtained based on slight temperature differences between normal tissue and pre-cancerous tissue that shows higher temperature because of higher blood vessel activity.

These applications are, however, limited to observing body surface area because the infrared camera systems are usually bulky and cannot be inserted into the human body. If an endoscopic system that can obtain thermal images inside the human body is developed, it will have significant applications in label-free early detection of cancer in various organs. For such
a system, coherent fiber bundles that transmit infrared images are essential, and the bundle should be thin and flexible for insertion into thin endoscopes. So far, some groups have developed coherent image bundles by using infrared light transmission fibers such as chalcogenide glass fibers [3,4] and polycrystalline silver-halide crystal fibers [5,6]. These fibers, however, usually have toxicity or chemical stability problems, and therefore they are difficult to insert into the human body.

Harrington et al. made coherent fiber bundles by using hollow-core optical fibers that transmit a wide infrared wavelength range, and they reportedly transmitted thermal images through the fiber bundle [7]. They used a rigid glass-capillary array as the base material and coated metal and dielectric films on the inner surfaces of the capillaries. Therefore, the fabricated bundles are not flexible. Because the diameters of the capillary holes are smaller than 150 μm, the transmission losses are high, and this limits the temperature sensitivity of the imaging system.

In this work, we fabricated a flexible coherent-fiber bundle for thermal imaging by putting small-bore hollow optical fibers together. In the acquisition of thermal images, differences in the transmission efficiency among fiber pixels were numerically compensated for high resolution imaging of body temperature.

2. Fabrication of hollow-fiber bundles

The image bundle consists of hollow optical fibers with inner metal and dielectric coating. With a proper dielectric thickness, reflectance on the inner wall of the hollow fiber is enhanced, leading to low transmission loss [8]. Therefore, we first designed a dielectric thickness suitable for measuring body temperature. Figure 1 shows a theoretical loss spectrum of hollow optical fibers with an inner dielectric film. In the calculation of the theoretical losses, a ray-optic model [9] was used, and the fiber used in the calculation had a 320-μm inner diameter and 1-m length. The dielectric coating was 0.37-μm thick, and the refractive index of the dielectric was 1.42 that of a cyclic olefin polymer (COP) [10]. The black-body radiation spectrum of 37°C is also shown in the figure, and with the 0.37-μm thick coating, the fiber covered most of the radiation wavelength range of body temperature.

Fig. 1. Theoretical transmission losses of dielectric-coated metal hollow fiber with 320-μm inner diameter and 500-mm length. Black-body radiation spectrum of 37°C is also shown.
Figure 2 shows loss spectra of a hollow optical fiber whose inner wall is coated with silver and COP. In the measurement, light from a Fourier-transform infrared spectrometer was coupled into the fiber by using a focusing mirror. The inner diameter of the fiber was 320 μm, and the length was 1 m. Although the coating thickness of COP was estimated as 0.32 μm, slightly smaller than that shown in Fig. 1, the low loss region covered the black-body radiation of body temperature shown in Fig. 1. In the measured spectra, absorption peaks of inner COP layer appear at around 2.5, 3.2, and 6.5 μm and one sees an absorption peak of carbon dioxide in the hollow core at 4.2 μm. Although some of these peaks are sharp and strong, these do not affect transmission of wavelength range around 9-10 μm that is the most important for measurement of body temperature as shown in Fig. 1. The figure also shows a loss spectrum of fiber that has a loop with a 50-mm radius at the center of the fiber. Additional losses due to the bending were smaller than 2 dB. Although the bending loss causes temperature difference in the detected value, the additional losses of each fiber in the bundle are the same because the diameter of the bundle is much smaller than the bending radius. Therefore, the bending does not affect temperature images to differentiate an affected tissues from normal ones. We confirmed that additional losses due to bending are small enough for body temperature imaging and this shows the fibers’ capability for medical applications where highly flexible fibers are needed.

We bundled 127 hollow optical fibers whose transmission characteristics are representatively shown in Fig. 2. The inner diameter of each fiber was 320 μm, and the length and total diameter of the bundled fiber were 470 mm and 6 mm. Figure 3 shows the flexibility of the bundled fiber; the minimum bending radius was around 35 mm. All the fibers were coherently aligned to deliver thermal images. Figure 4 shows the distal end of a bundled fiber that was fluorescent lighted from the other end. The difference in color of transmitted light is due to slight variation in the coating thickness of inner polymer film and this does not affect the transmission property in the infrared. To protect the hollow core from dust and water, the distal end can be sealed with a polyethylene film that has little absorption in the infrared.
3. Acquisition of thermal images

In experiments, an infrared image of a sample was formed on the distal end of the bundled fiber by using a ZnSe lens. The image transmitted through the fiber was observed by a thermographic camera with an uncooled micro-bolometer array of 320 × 480 pixels. Figure 5 shows an observed image, transmitted through the bundle, of a hot plate having a uniform temperature of 70 °C. In this measurement, because the distal end of the bundle is put very close to the hot plate with distance around 3 mm, the end part is warmed by the heat radiation and therefore, the fiber itself emits infrared radiation. We experimentally confirmed that this does not affect measurement of the target. By using a heater, we intentionally heated the bundle up to 120 °C and found no difference in the measured infrared image from the bundle. This is because of mode filtering effect of hollow optical fibers. Hollow optical fiber only transmits very low-order modes because of the small numerical aperture that is reportedly only a few degrees in full angle. Therefore, most of infrared radiation emitted from the fiber’s inner surface is lost while transmitting in the fiber. However, the output end should be kept at room temperature because the emission from the output end wall affects the measured true image.
Due to variations of transmission efficiency among the fibers, the observed intensity was not uniform as seen in Fig. 5. To compensate the variation, we measured the intensity of each fiber pixel by using an image processing function of MATLAB to obtain weight functions that are applied to raw images to produce thermal distribution in measurements of thermal images of samples. First, from the observed image of the hot plate, each fiber was automatically located and the light intensity of each fiber was calculated by integrating energy intensity transmitted through the fiber bore to obtain the weight function. Second, the same integration was performed for the sample image, and the weight was applied to obtain a measured value. Finally, each intensity was aligned in a hexagonal lattice to produce the final thermal image.

Figure 6 shows an observed thermal image of a fingertip. By use of the hollow-fiber bundle and the numerical compensation, the body temperature can be remotely measured. Because the edge of the nail can be differentiated by the difference in emissivity between the nail and skin, the thermal resolution was around 1°C. With such a high resolution, one can differentiate inflamed and normal tissues inside the human body.

Figure 7 shows a thermal image of a dorsal hand vein. The image of the vein that was directly taken by the thermographic camera (left picture) can be seen in the thermal image observed through the bundled fiber (right picture). In this measurement, the nonuniformity of the fibers are cancelled by using the method shown above. The magnification factor of the
lens system was 1/10 and the spatial resolution of the system was around 3 mm. By introducing the bundled hollow optical fiber inside a body with an endoscope, one can observe an image of the blood flow on the surfaces of internal organs. This enables early detection of tumors, where high blood flow is usually observed.

Fig. 7. Thermal images of dorsal hand vein observed through hollow fiber bundle (right) and directly by thermographic camera (left).

4. Conclusion

A flexible and coherent bundle of hollow optical fibers was fabricated for infrared thermal imaging. For acquisition of thermal images, differences in the transmission efficiency among the fibers were numerically compensated to obtain a high temperature resolution of 1°C for measuring body temperature. As far as we know, this is the first report on observation of body surface temperature by using a hollow-fiber-based bundle. This observation became possible due to high transmission efficiency of the hollow optical fibers and a newly developed image processing technique. In a lens system with 10-fold magnification and hollow fibers of 320-μm inner diameter, the spatial resolution is around 3 mm. The system enables observation of the surface temperature of inner organs and blood flow of the surface when the fibers are introduced into the human body with an endoscope. To obtain higher resolution in a wide observation area, downsizing the fiber diameter is necessary. However, this causes higher loss and, therefore, further reduction of transmission losses of hollow optical fiber is essential.