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Microstructured Arrayed Microfluidic Waveguide Structure for Infrared Radiation Focusing and Transfer

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Abstract: A microstructured arrayed microfluidic waveguide structure for infrared radiation focussing and transfer is proposed and demonstrated. The arrayed waveguide structure comprises Masterbond UV-curable epoxy UV15 optimised using ZEMAX optical design software to achieve high efficiency of heat capture through far-infrared light focussing and subsequent absorption of the radiation on a centralised fluid medium. A high degree of alignment of the precision-positioned fluidic microchannels with the symmetry axes and the focal plane locations of the cylindrical microlens array is demonstrated, which maximises the efficiency of absorption of the incident IR light energy within the moving fluid. Observation of ink flows through the initial device prototype confirms the suitability of our microfluidic channel fabrication technology for the transfer of far-infrared light (heat) transfer. This microstructured arrayed waveguide structure has application for development of a textile fabric that enhances surface heat removal.

Index Terms: MicroPhotonics, Microfluidics, Optics, Surface Heat Removal, Cool Clothing.

1. Introduction

Under resting thermoneutral climatic conditions (i.e., 18–22°C), ~90 Watts of metabolic heat energy is both produced and removed from the body through the heat transfer processes of convection, conduction, and radiation. Under these conditions, heat transfer is balanced, and a homeostatic life-sustaining core body temperature of about 37°C is maintained. Under these thermoneutral conditions, radiative heat loss in the infrared region of the electromagnetic spectrum approximates 90 W on a resting naked human body. At an ambient temperature of 30°C however, radiative heat loss is reduced to ~45 W, which instead leads to heat gain and a resulting increase in core body temperature. To solve this problem, humans evolved the efficient heat removal mechanism of sweat evaporation, which liberates 2270 kJ of energy per litre of sweat evaporated, or 630 Watts of heat energy over a one hour period. This mechanism of heat removal with sweating works efficiently to control body temperature under conditions conducive to evaporation.

There are situations however where the process of heat loss with sweating becomes impaired. Examples include 1) conditions of high environmental humidity (high vapour pressure), such as that experienced in the tropics, 2) when an insulate layer of clothing forms a barrier separating the skin from the surrounding environment (i.e., thick clothing), and 3) with aging, where sweat rate is lowered. All of these examples can lead to a situation known as uncompensatable heat stress, which causes core body temperature to rise uncontrollably [1]. An increase in core temperature of only 1°C above normal is perceived as uncomfortable, causes dehydration due to sweating, and lowers physical work capacity. Sustained body temperatures of more than 5°C above normal are fatal [1].

The heat removal problem affects a number of important occupations throughout the world, including the military, mining industry and fire service, all which require a workforce to wear protective clothing not conducive to sweat evaporation [2, 3, 4, 5]. Indeed, the creation of a practical heat removal device for these workers has challenged scientists to date. As noted in the Australian Bureau of Transport and Regional Economic report, "a significant breakthrough in reducing heat strain while wearing (protective) clothing in field conditions is needed" [6].

Such a breakthrough in heat removal efficiency could be possible through the combined technologies of microphotonics and optics. The infrared radiation emitted by the human body at the mid-infrared wavelength during heavy exercise can be seen as a bright "light bulb", emitting tens of Watts of invisible light.

In this paper, we propose and demonstrate the principle of a novel photonic heat-transfer fabric to control human body temperature using the integrated technologies of microphotonics and optics. We also show that the removal of body heat can be assisted by concentrating the emitted infrared radiation for absorption on a liquid medium moving through microfluidic channels engineered within a textile material. Thus, "reverse-action wetsuits" can be realised by combining modern photonics and optical technology. Our approach could offer a novel technical solution for the heat removal problem experienced by the industrial workforce and the elderly, and may have application for the design of a lightweight textile material that could be integrated into a garment to enhance body heat removal for prolonged periods. Such a garment has the capacity to revolutionise survival clothing for the military, the fire service and the resource industry.

2. Microstructured Arrayed Microfluidic Waveguide Structure Design and Fabrication

One- and two-dimensional interferometric lithography processes have successfully been used to fabricate microfluidic channels of cross-section areas as small as 10x10 μm^2. High-resolution imprint lithography has recently emerged as a very promising technology for the fabrication of Integrated Circuits (ICs) and nanofluidic devices [7]. However, one of the challenges facing such processes is the precise etching of microfluidic channels using cost-effective high-volume fabrication. Recently, new techniques for the application-specific control of fluid flows in microfluidic channels have successfully been demonstrated [8, 9].

The principal design diagram of the proposed photonic fabric structure is shown in Figure 1. It consists of an array of a cylindrical microlens array that focuses the IR radiation onto arrayed microfluidic channels etched onto an epoxy layer deposited on top of the 75mm×25mm substrate. The removal of heat is assisted by concentrating the emitted IR radiation for absorption on a liquid medium moving through the arrayed microfluidic channels. The key feature of the fabric design shown in Fig. 1 is the high degree of alignment of the precision-positioned arrayed fluidic microchannels with the symmetry axes and the focal plane locations of the cylindrical microlenses. This is necessary for maximising the efficiency of absorption of the incident IR light energy within the moving fluid. A thermoelectric cooler (TEC) in conjunction with a heat sink can be used as the means for cooling the fluid circulating in the fluidic loop. The relationship between the cross-section of the microfluidic channels and the cooling power required is optimised by maximising the IR radiation that is focused at different positions along the fluid flow.

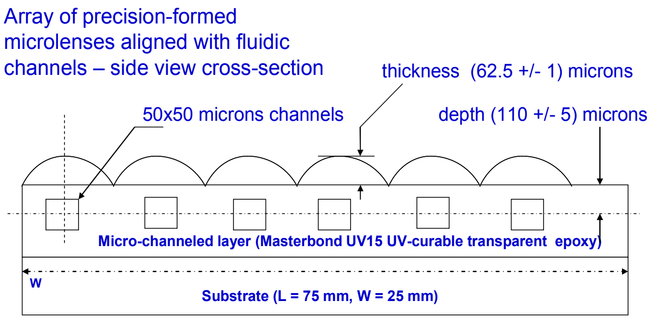

Fig. 1. Principal diagram of the device design (cross-section of a patch of the proposed heat transfer fabric).

The optical parameters of the fabric prototype were optimised using ZEMAX optical design software to achieve the high efficiency of heat capture through the far-infrared light focussing and subsequent water absorption of the radiation (Figure 2). The radius of curvature of the cylindrical microlenses was 62.5 μm. This was chosen to enable the imprint mask to be realised using conventional optical fibres, leading to cost-effective and precise imprint mould. The optimum distance between the microlenses and the microfluidic waveguides was 85 μm and the waveguide cross-sectional area was 50μm ×50μm.

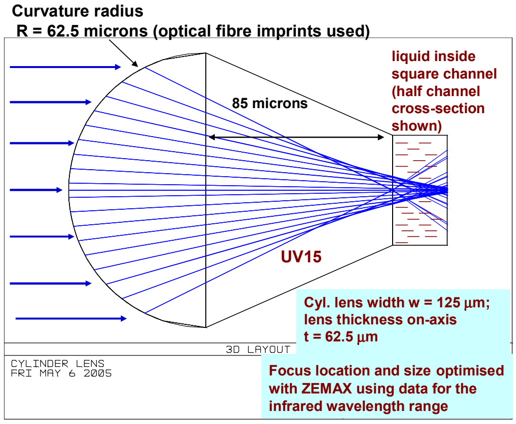

Fig. 2. Optical parameters of the fabric optimised using ZEMAX optical design software to achieve the high efficiency of heat capture through focussing and fluid absorption of the IR radiation.

Fibre imprint moulding and epoxy re-flow technologies were used to fabricate the heat-transfer fabric structure shown in Figure 3. The re-flow microfabrication process involved the formation of cylindrical lenses by melting and later re-solidifying the solid-phase rectangular microstripes of adhesive material (NOA73) arranged on an optical substrate. The re-flow technology provided a high degree of alignment of the microlenses and microfluidic channels. The principal challenge was to realise a good degree of optical alignment and suitable lens surface qualities. The experimental setup for demonstrating the heat-transfer fabric is shown in Figure 4. Note that a commercial Bartels Mikrotechnik mp5 USB-controllable microfluidic pump was used for fluid propagation.

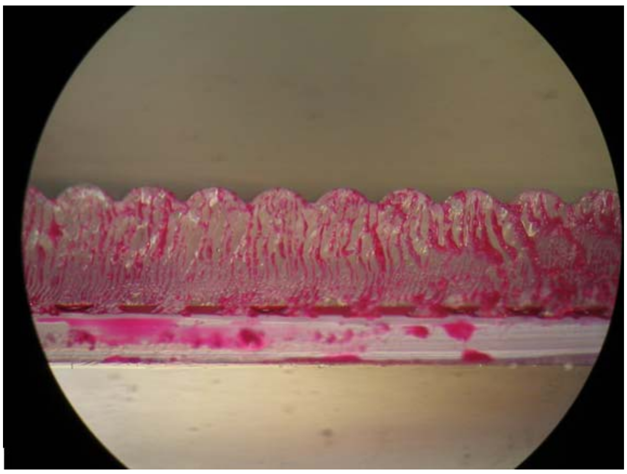

Fig. 3. Microphotograph of the fabric prototype made of NOA73 adhesive using reflow technology.

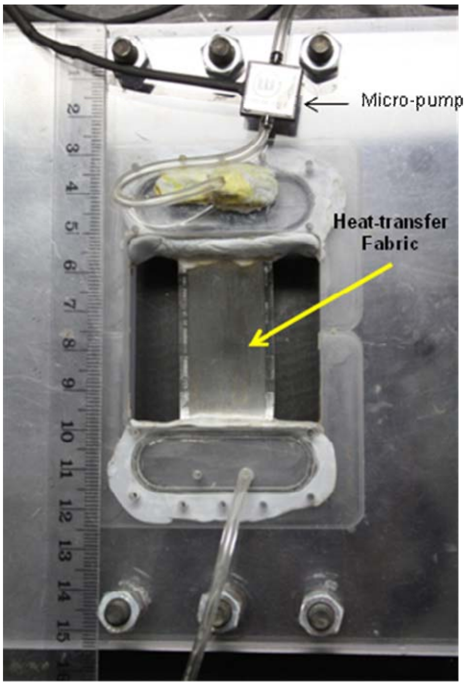

Fig. 4 Developed heat-transfer fabric prototype.

3. Optical Quality Inspection

Figure 5 shows the optical quality inspection of the fabric prototype. The cylindrical microlens surfaces were inspected under the microscope to reveal their surface features and to estimate the degree of microlens array alignment. A diffraction pattern generated by the microlens array under the He-Ne laser illumination showed the expected regular features, thus demonstrating the periodicity of the array and confirming the suitability of the adopted microphotonic technology to fabricate high-quality heat-focusing cylindrical lens arrays. A close-up of the microscope field of view showing the excellent lens surface quality is shown in Figure 6, where the HeNe laser light was used to illuminate the heat-transfer fabric. Figure 6 demonstrates the alignment/parallelism, lateral spacing uniformity, surface quality and the accurate curvature of the fabricated microlens array. Further investigations involving thermodynamic modelling, optimisation and characterisation of the device performance in terms of IR absorption efficiency and fluid throughput are ongoing.

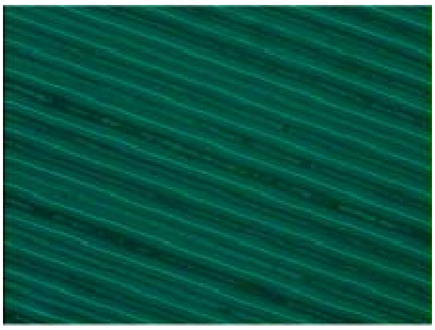

Fig. 5. Results of preliminary prototype manufacture showing the micro-molded preliminary test prototype made with optical fibre imprints using UV15 epoxy as a base material.

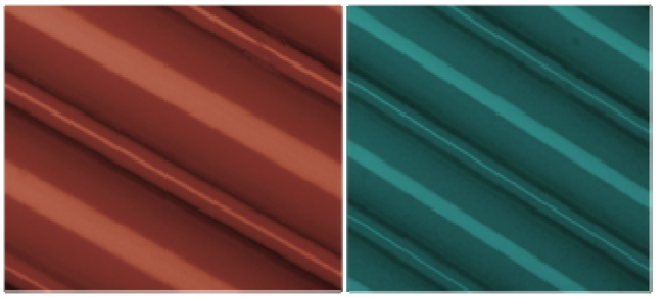

Fig 6. A close-up microscope image showing the excellent surface quality and periodicity of the cylindrical lens array.

Figure 7 shows the experimental setup for the optical inspection of the fabricated heat-transfer fabric. The illumination of the cylindrical microlens array (acting as a diffraction grating) with a Helium-Neon (HeNe) laser light resulted in a periodic diffraction pattern which confirmed the array periodicity with minimum irregularities.

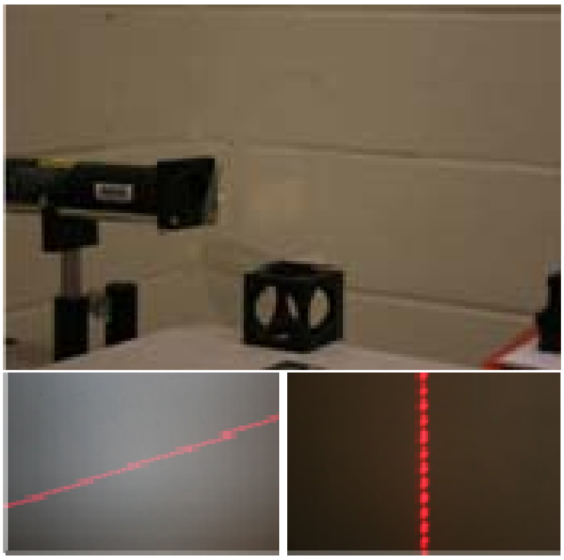

Fig. 7. Experimental setup demonstrating the uniformity of the microlens array (top). The illumination of the microlens array with a HeNe laser generated a regular spot array (bottom).

The ability of the heat-transfer fabric prototype to propagate the flow of liquid within its microchannels was also tested. Ink flows through the microfluidic channels are shown in Figure 8, confirming the suitability of the reflow technology to fabricate microfluidic channels for heat transfer. Future work will focus on full characterisation of the integrated heat transfer fabric system, based on real-time monitoring of human body temperature during laboratory exercises in a climate chamber with and without environmental protective gear, as well as the identification of the optimum fluid required and the microfluidic channel dimension range that enable optimum laminar flow with minimum viscosity loss.

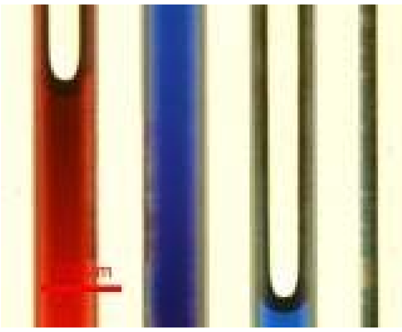

Fig. 8. Microphotograph of ink solutions propagating through the microstructured arrayed microfluidic waveguide prototype.

6. Conclusion

We have proposed and demonstrated the principle of a microstructured microfluidic waveguide structure for infrared radiation focussing and transfer. The waveguide structure, comprised of Masterbond UV-curable epoxy UV15 achieved high efficiency of heat capture through far-infrared light focussing and subsequent absorption of the radiation on a centralised fluid medium. We have shown that the high degree of alignment achieved through the use of precision-positioned fluidic microchannels, symmetry axes and focal plane locations, is necessary to maximise the efficiency of absorption of the incident IR light energy within the moving fluid. Various ink flows through the initial device prototype have confirmed the suitability of our microfluidic channel fabrication technology for the transfer of infrared light. The heat-transfer fabric structure has application in heat removal and, if developed into a textile, would be an important step forward for the human heat removal problem.

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