Polymer Photonic Crystal Membrane for Human Body Thermoregulation

*Mohamed Boutghatin, Salim Assaf, Michèle Carette, Vincent Thomy, Abdellatif Akjouj, Bahram Djafari- Rouhani, Yan Pennec**

Institute of Electronic, Microelectronic and Nanotechnology (IEMN), Université de Lille

Villeneuve d'Ascq, France

*e-mail : mohamed.boutghatin@univ-lille.fr; salim.alhajj-assaf@univ-lille.fr; michele.carette@univ-lille.fr; vincent.thomy@univ-lille.fr; abdellatif.akjouj@univ-lille.fr; bahram.djafari-rouhani@univ-lille.fr; *yan.pennec@univ-lille.fr*

***Abstract*—We study the optical properties of a polymer photonic membrane to keep the human body in thermal comfort. We show theoretically that the periodic structuration of the membrane with air holes modulates the optical response in the Mid-Infrared range. We found that the modulation of the optical spectrum allows to decrease the required ambient temperature by about 0.5 °C to maintain the normal skin temperature of 34 °C. The structured membrane is flexible and can easily be added to usual textiles.**

Keywords-photonic membrane; Mid-Infrared; thermal comfort.

I. INTRODUCTION

A large part of the energy consumed is used to regulate the temperature of residential buildings. Reducing this consumption will have a positive impact on the economy and the environment. In previous studies, the importance of personal thermoregulation was investigated and demonstrated in different ways [1][2]. Photonic crystals have been recently proposed to control the propagation of electromagnetic waves in the Mid-Infrared range for several applications from thermophotovoltaic systems to thermal textile [3]. For radiative cooling, Raphaeli et al. presented a metal-dielectric photonic structure, reflective in the visible and having high emissivity in the Mid-Infrared [4]. More recently, we have demonstrated the efficiency of a structured polymer membrane to maintain an individual thermal comfort in indoor rooms [5]. Our objective here is to demonstrate that a polymer membrane can act both as a sensor by the modification of its structural parameters and as a passive actuator by modifying its thermal properties.

In this work, we propose to study numerically a polyethylene (PE) membrane drilled with air holes following a triangular array, as illustrated in Figure 1. The structured membrane is characterized by three geometrical parameters, the thickness (h), the diameter of the hole (D) and the period of the array (P).

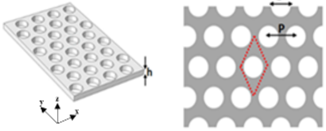

Figure 1. 3D and top-view representation of the polymer photonic membrane. The red dotted lines represent the elementary unit cell.

In section II, we discuss the effect of structuration of the PE membrane in the Mid-IR range. In section III, we investigate the thermal properties of the photonic membrane to maintain the thermal comfort of the human body.

II. OPTICAL PROPERTIES

We performed the numerical calculation with the help of the Finite Element Method (FEM), considering an incident wave coming from the human body and launched in air medium normally to the photonic membrane. To simulate the interaction wave-photonic membrane, we used the commercial COMSOL software to solve the Maxwell equations. The elementary unit cell is defined Figure 1, where we applied the Periodic Boundary Conditions (PBC) along the two directions x and y to build the periodic membrane. We thus calculated the reflection (R) and transmission (T) coefficients and deducing the absorption coefficient (A) by the formula A = 1 – R – T. Figure 2(a) shows the evolution of the reflection R (black), transmission T (blue) and absorption A (red) in the wavelength range [5-15 μm] for a non-structured membrane of thickness h = 4 μm. The blue light shaded area corresponds to the human body radiation calculated at 34 °C following the Planck law. One can see that, for a thickness h = 4 μm, the transmission is comprised between 80% and 100% with an average absorption less than 10%. It means that the PE membrane is almost transparent in the Mid-IR.

Figure 2 (b) reports the same calculation of the coefficients when the membrane is structured with the set of geometrical parameters: h = 4 μm, D = 5.5 μm and P = 7 μm. The comparison between the spectrum of the simple membrane (a) and the structured one (b), shows the occurrence of new peaks and dips between 6 and 7 μm (see Figure 2(c)). It means that the structuration clearly affects the scattering coefficients at low wavelength. The modulus of the calculated electric field shows that the two peaks (A and C) correspond to guided modes inside the membrane. With respect to the middle plane of the membrane, the first one (A) is antisymmetric while the second one (C) is symmetric. The peak B corresponds to a mode confined in the air hole. This latter gives rise to an asymmetric peak and comes from the interaction of the localized mode B with the incident wave, known as a Fano-like resonance.

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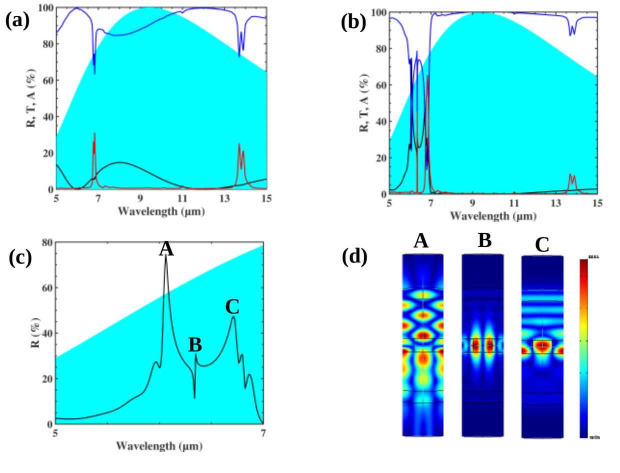

Figure 2. (a, b) Reflection (black), transmission (blue) and absorption (red) spectra for the (a) non structured and (b) structured PE membrane with the geometrical parameters: h = 4 µm, D = 5.5 µm and P = 7 µm. (c) Magnification of the reflection curve in (b) in the wavelength range [5-7] µm. Human body radiation at 34 °C is indicated by the shaded region. (d) Snapshots of the modulus of the electric field for the three peaks of reflection A, B and C.

In order to show the effect of geometrical parameters on the photonic membrane spectrum (that could happen when using active polymer reacting to parameters, such as temperature or humidity), we homothetically increase the three parameters h, D and P. Figure 3 shows the spectrum for the set of geometrical parameters: h = 5.1 µm, D = 7.1 µm and P = 9 µm.

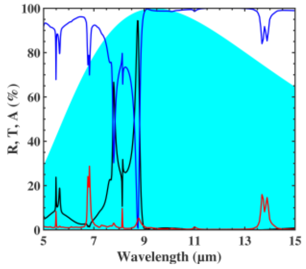

Figure 3. Reflection (black), transmission (blue) and absorption (red) spectra for the structured PE membrane with the geometrical parameters: h = 5.1 µm, D = 7.1 µm and P = 9 µm.

One can see that the photonic effect has been shifted to higher wavelengths. With these chosen parameters, peaks and dips now occur in the vicinity of 9 µm. Therefore, a variation of the geometrical parameters offers the possibility to span the full range of radiation of the human body at the skin temperature 34 °C.

III. THERMAL PROPERTIES

We then investigated the thermal properties of the photonic membrane, considering an unidimensional heat model previously developed [2]. The two volumes of control in our case are: the human body standing and relaxed and the PE membrane. The emissivity of the human body and environment is assumed to be equal to the unity. In the thermal model, we have considered all conduction, convection and radiative heat flows between the human body and the indoor room, through the photonic membrane. The resolution of the thermal equations leads to a balance where the temperatures depend on the scattering coefficients calculated in the previous part.

To estimate the efficiency of the photonic membranes we proceed to the calculation of the required ambient temperature to achieve the skin temperature of 34 °C. This latter is considered as a reference for a comfort feeling of the human body.

Figure 4 represents the evolution of the required ambient temperature as a function of different set of parameters of the photonic membrane. The blue curve corresponds to the ambient temperature for a non-structured membrane, drawn as a reference. For the structured one, we have considered different scaling factors, taking from reference [5]: α_1 (h = 4 µm, D = 5.5 µm, P = 7 µm), α_3 (5.1 µm, 7.1 µm, 9 µm), α_5 (6.3 µm,8.6 µm, 11 µm), α_7 (7.4 µm, 10.2 µm, 13 µm) and α_9 (8.6 µm, 11.8 µm, 15 µm). Figure 4 shows that for the non-structured membrane with a thickness of 8.6 µm (α_9), the comfort skin temperature of 34 °C can be reached with an ambient temperature of 25.5 °C.

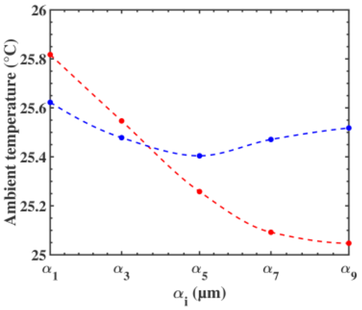

Figure 4. Evolution of the required ambient temperature to achieve 34 °C as a function of geometrical parameters for a skin covered with a non-structured (blue) and structured (red) membrane.

On the other hand, when the same membrane is drilled with air holes of diameters 11.8µm and a period of 15 µm, an ambient temperature of 25 °C is sufficient to achieve the skin comfort. It means that the latter structured membrane minimizes the necessary external temperature to maintain the human body in thermal comfort by almost 0.5 °C.

IV. CONCLUSION AND FUTURE WORK

In conclusion, we have demonstrated theoretically that a change in the structuration parameters of a polymer membrane can modulate the optical coefficient in the Mid-IR range. We show that, with an appropriate design of polymer photonic membrane, we can efficiently modulate the thermal radiation emitted from the human body. Compared to a regular PE textile, the photonic membrane maintains the thermal comfort of the human body with a lower ambient temperature of 0.5 °C. In addition, we seek to study photonic membranes based on active polymer, sensitive to ambient temperature, to study a textile membrane which acts both as a sensor and a passive actuator.

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REFERENCES

[1] P.-C. Hsu et al., “Personal Thermal Management by Metallic Nanowire-Coated Textile”, Nano Lett., vol. 15, no 1, p. 365-371, janv. 2015, doi: 10.1021/nl5036572.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, pp. 68–73, 1892,

[2] J. K. Tong, X. Huang, S. V. Boriskina, J. Loomis, Y. Xu, and G. Chen, “Infrared-Transparent Visible-Opaque Fabrics for Wearable Personal Thermal Management”, ACS Photonics, vol. 2, no 6, pp. 769-778, juin 2015, doi: 10.1021/acsphotonics.5b00140.

[3] W. Li and S. Fan, “Nanophotonic control of thermal radiation for energy applications [Invited]”, Opt. Express, vol. 26, no 12, p. 15995, juin 2018, doi: 10.1364/OE.26.015995.

[4] E. Rephaeli, A. Raman, and S. Fan, “Ultrabroadband Photonic Structures To Achieve High-Performance Daytime Radiative Cooling”, Nano Lett., vol. 13, no 4, pp. 1457-1461, avr. 2013, doi: 10.1021/nl4004283.

[5] S. Assaf et al., “Polymer photonic crystal membrane for thermo-regulating textile”, Sci Rep, vol. 10, no 1, pp. 9855, déc. 2020, doi: 10.1038/s41598-020-66731-1.