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Rahul Kumar
Northumbria University

Wei Han
Technological University Dublin

Dejun Liu
Technological University Dublin

See next page for additional authors

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Authors

Rahul Kumar, Wei Han, Dejun Liu, Wai Pang Ng, Richard Binns, Krishna Busawon, Yong Qing Fu, Zabih Ghassemlooy, Christopher Underwood, Khamid Mahkmov, Jinhui Yuan, Chongxiu Yu, Huazhong Shu, Xing Ao Li, Tuan Guo, Gerald Farrell, Yuliya Semenova, and Qiang Wu Prof.

Singlemode-multimode-singlemode fibre structure for phase transition monitoring in phase changing materials (invited paper)

Rahul Kumar[1], Wei Han[2], Dejun Liu[2], Wai Pang Ng[1], Richard Binns[1], Krishna Busawon[1], Yong Qing Fu[1], Zabih Ghassemlooy[1], Christopher Underwood[1], Khamid Mahkmov[1], Jinhui Yuan,[3] Chongxiu Yu,[3] Huazhong Shu[4], Xing Ao Li[4], Tuan Guo[5], Gerald Farrell[2], Yuliya Semenova[2], and Qiang Wu*

[1] Faculty of Engineering and Environment, Northumbria University, Newcastle Upon Tyne, NE1 8ST, United Kingdom
[2] Photonics Research Centre, Dublin Institute of Technology, Kevin Street, Dublin 8, Ireland
[3] State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing, China
[4] Key Laboratory for Organic Electronics & Information Displays (KLOEID), Institute of Advanced Materials (IAM), School of Materials Science and Engineering (SMSE), Nanjing University of Posts and Telecommunications (NUPT), Nanjing 210023, PR China
[5] Institute of Photonics Technology, Jinan University, Guangzhou 510632, China

*Corresponding author: qiang.wu@northumbria.ac.uk

Abstract. A platinum-coated singlemode-multimode structure is investigated in this paper as an optical fibre sensor (OFS) to monitor the phase transition of a phase change material (PCM). Paraffin wax has been used as an example to demonstrate the sensor's performance and operation. Most materials have the same temperature but different thermal energy levels during the phase change process, therefore, sole dependency on temperature measurement may lead to an incorrect estimation of the stored energy in PCM. The output spectrum of the reflected light from the OFS is very sensitive to the bend introduced by the PCM where both liquid and solid states exist during the phase transition. The measurement of strain experienced by the OFS during the phase change of the PCM is utilized for identifying the phase transition of paraffin wax between the solid and liquid states. The experimental results presented in this paper show that the OFS can measure the phase change point of paraffin wax and the sensor with a multimode fibre length of 10 mm measured the phase transition temperature range from 37.8 ºC to 57.7 ºC.

1. Introduction

Solid-liquid phase change materials (PCMs) have been widely used in latent heat thermal storage systems for heat pumps [1-2], solar engineering [3], and spacecraft thermal control [4]. A simple and common application of PCM can be seen in thermally insulated water bottles, where the PCM surrounded by water melts and is used to store the heat from the hot water. The stored heat is then released back to the water at a slower rate as the PCM solidifies so as to maintain a desired water temperature over a longer period of time than would be the case if a simple insulator was used instead of a PCM. There are a large number of PCMs, which melt and solidify over a wide range of temperatures, which are attractive for a wide number of applications [4, 5]. The practical realization of an efficient PCM-based thermal energy management system requires an in-depth understanding of the PCM behavior during melting and solidification stages. Solidification can occur below the expected phase transition temperature, a phenomenon referred to as under-cooling [6]. Temperature measurements are widely used to measure the amount of stored thermal energy in PCMs. However, in many cases at the solid-liquid phase (SLP) change state, most materials have the same temperature but different energy levels. For example, at 0 ºC, 1 gram of liquid water has 333.55 Joules more energy than that of the solid ice. Therefore, sole dependency on temperature measurement alone may lead to an incorrect estimation of the stored energy in the PCM, particularly in a large PCM-based energy storage system. It is hence necessary to develop a new technique to monitor the SLP change by determining the start and end points of phase changes, a measurement which cannot be undertaken by traditional temperature sensors. One possible option is the use of optical fibre sensor technology.

Singlemode-multimode-singlemode (SMS) fibre sensors [7, 8] possess a simple fabrication process and low cost with high sensitivity, have attracted wide research interest in recent years for measurements of strain [9], temperature [10], refractive index [11], and chemical concentrations [12]. Our previous investigations demonstrated that an SMS sensor is very sensitive to even minor bending forces applied to it [13]. In a PCM at the SLP change point, small local variations in the state of material surrounding the fibre result in slightly different forces being applied to different locations on the SMS fibre sensor, since these local variations occur on a spatial scale similar in size to the dimensions of the SMS sensor. The result is that micro bends occur along the length of the SMS sensor and in turn this leads to a significant wavelength shift $\Delta\lambda$ in the output spectrum of the SMS fibre sensor. In this paper we experimentally investigate an SMS fibre based sensor structure as a better and more accurate means to monitor the phase change of a PCM. The well-known PCM paraffin wax is used as the host material.

2. Principle and Experiments

Figure 1 shows a schematic diagram of a reflective singlemode-multimode (SM) fibre structure.

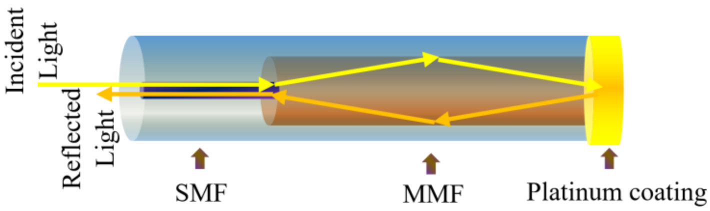

Figure 1 Schematic diagram of a reflective SM fibre structure

As shown in Figure 1, when light injected from singlemode fibre (SMF) into the multimode fibre (MMF), multiple high-order modes will be excited and propagate along the MMF. Because the MMF end coated with platinum which will reflect the light and couple it back to the SMF. These multiple modes will interference each other resulting in transmission dips and peaks in the output spectral response, which depend on the surrounding environment, i.e., local temperature, longitudinal strain and the fibre bending.

Experiments were carried out by inserting the above structure sensor into paraffin wax sample to monitor phase change point of the wax. In this experiment, a reflective SM fibre sensor with MMF length 10 mm was used. The reflective SM structure is fabricated by fusion splicing a short length of MMF (AFS105/125Y) with a conventional SMF (SMF28), and coating the unconnected MMF end with a thin layer of platinum (10 nm thickness). A thermocouple is placed as close as possible to the

SM sensor to measure the temperature of wax. Figure 2 shows the measured wavelength as a function of temperature (30.0 °C to 70.0 °C) of the platinum coated SM fibre structure. The measurements were carried out by increasing and then decreasing the temperature of the paraffin wax measured with the thermocouple within the range of 30.0 ºC – 70.0 ºC.

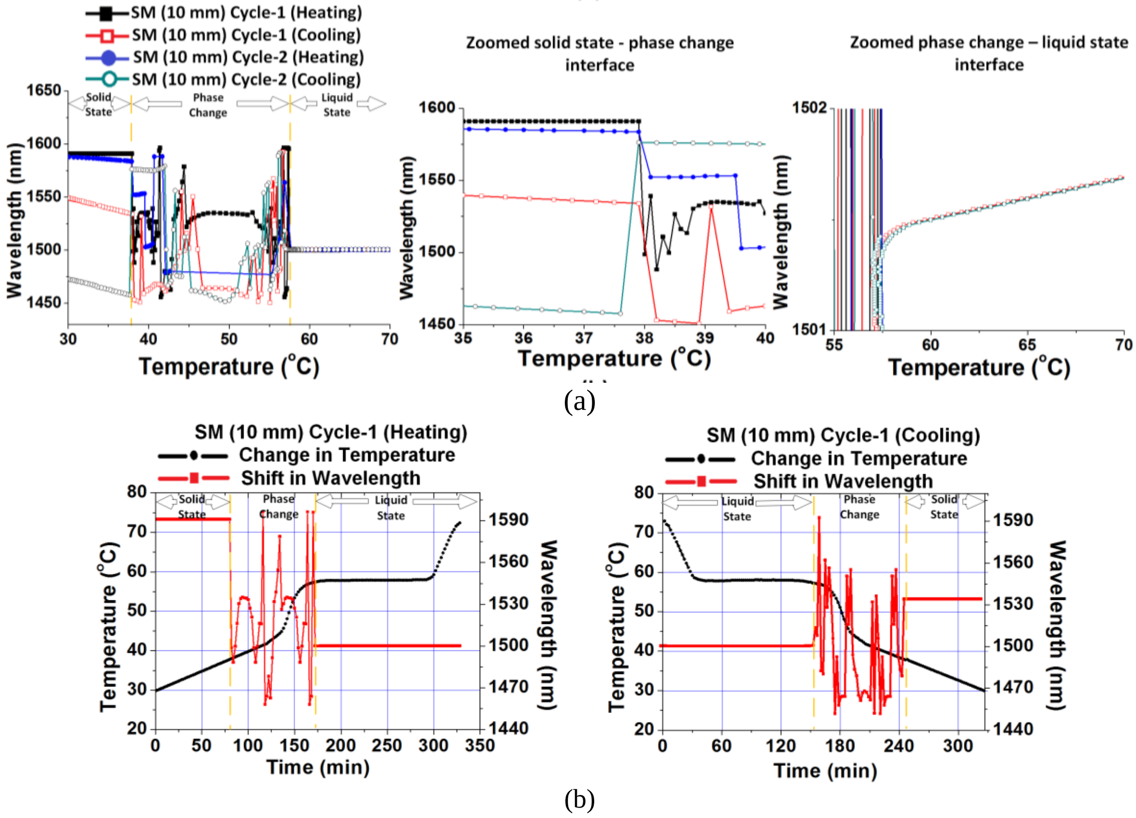

Figure 2 (a) Measured wavelength shift vs. the temperature for the platinum coated SM structure and (b) comparison between the measured temperature and the wavelength shift as a function of time. Measurements are taken by increasing and then decreasing the temperature of the paraffin wax over a range of 30.0 ºC – 70.0 ºC.

As shown in Figure 2(a), there are two temperature (T) ranges (i.e., 30.0 ºC < T < 37.8 ºC and 57.7 ºC < T < 70.0 ºC) where the paraffin wax is in a solid and liquid states respectively and where the wavelength responses are fairly linear but with different slopes. The result indicates that the shift in the spectral dip within the temperature ranges used is mainly due to the temperature-induced strain on the sensor immersed in solid and liquid paraffin, respectively. Of most interest is the temperature range 37.8 ºC < T < 57.7 ºC, where both solid and liquid states exist simultaneously and where the stress applied along the length of the fibre sensor is not uniform which in turn induces random micro-bends in the SM fibre sensor, thus resulting in a random wavelength shift with temperature. Note that, the abrupt nature of the changes in the spectral wavelength is likely due to the random lateral force applied to the sensor by the solid-liquid mixed phase states of the wax, which leads to an abrupt micro-bending state at a random position with a random radius along the MMF section of the fibre sensor. Figure 2 also shows a good agreement in terms of the temperature range within which the phase change takes place for the measurements for both cycles 1 and 2 (i.e., increasing and decreasing T) as well as a similar response for each cycle. Note that, for all the measurements taken at T > 57.7 ºC the wavelength profiles are the same. This is because with the wax in the liquid state the forces acting upon the sensor are small and homogenous, resulting in the absence of micro bending of the SM fibre sensor. However, for T < 37.8 ºC the wax is in a solid state resulting in micro bending of the sensor. Note that, the micro bending state appears again when the wax cools down from the liquid to the solid phase state, thus resulting in a different but linear wavelength shift as a function of temperature (i.e., for all four sets of measurements for T < 37.8 ºC). For T < 37.8 ºC, the wax is fully solidified and hence the temperature induced micro bending in the SM fibre sensor is relatively small, thus resulting in a linear wavelength response.

Figure 2(b) shows the measured temperature and the wavelength shift as a function of time for paraffin wax for 30.0 ºC < T < 73.0 ºC for heating and cooling cycles. During the continuous heating process temperature increases linearly for up to t = 135 mins and then changes rapidly for the next 40 mins reaching a steady state value of ~57.7 ºC at t = 175 mins. Following this, temperature continues to increase in a linear manner. The first rise in temperature is because the solid wax transfers heat with a relatively low thermal conductivity, which results in a significant ΔT between the bottom of the wax (located near the heat source) and the measured point. After 135 mins, the wax enters the phase change state where both liquid and solid will coexist, which significantly increases the thermal conductivity and consequently the abrupt changes in temperature. The constant T during $175 < t < 295$ mins is due to the liquid and solid having the same temperature, where the additional heat energy absorbed by the wax is used to change the phase state from solid to liquid rather than alter the temperature. Beyond $t > 295$ mins all the wax has changed from solid to liquid and the absorbed heat begins to increase the wax temperature. The dip wavelength of the reflective SM sensor displays a random shift with no linear relationship with the changes in temperature, for $135 < t < 175$ mins and 37.8 ºC < T < 57.7 ºC. This is because of the aforementioned paraffin wax induced random micro-bending state of the SM sensor due to simultaneous existence of solid and liquid phase states of the wax. When the temperature of the paraffin wax is decreased, it shows the opposite response for both temperature and wavelength shift to that of increase temperature.

3. Conclusion

In this paper, a reflective SM structure was proposed for measuring the different phase state of the paraffin wax. During the phase change of the paraffin wax both solid and liquid states existed simultaneously, which result in random lateral forces applied onto the SM structure, thus introducing the abrupt micro-bending in the sensor. The micro-bending of the reflective SM sensor introduced an abrupt wavelength shift in the spectral response of the sensor. Based on the aforementioned principle, the proposed sensor was able to detect the start and end points of phase change of the material.

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