Real-time two-dimensional pressure sensing for patient monitoring based on optical coupling between crossing polymer optical fibres

Real-Time Two-Dimensional Pressure Sensing for Patient Monitoring based on Optical Coupling between Crossing Polymer Optical Fibres

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Abstract: Position detection is a key function needed for monitoring patients with sleep-related movement disorders. Tools are urgently needed to obtain a detailed patient-friendly long-term assessment of sleep-related movements in the home situation. We present an optical two-dimensional pressure sensing system for real-time patient monitoring that is based on optical coupling between crossing polymer or plastic optical fibres (POFs) and can easily be placed under a mattress in a home environment. Because the system deploys a grid of standard 1 mm diameter Step Index PMMA POF, it is low-cost, robust, flexible, compact, waterproof, scalable, not affected by external electrical fields, nor does it generate any electrical fields. Moreover, an alternative simple pressure sensitive POF crossing construction, based on local fibre bending is presented, which is more sensitive and more robust than crossing fibres left intact.

1. Introduction

Sleep-related movement disorders form a spectrum of invalidating diseases, characterized by abnormal motor function during sleep. Tools are needed to obtain a detailed long-term assessment of sleep related movements in the home situation, in order to reach a precise clinical diagnosis, make an estimation of severity and to enable treatment follow-up. In our POF conference 2016 invited paper "Robust Two-Dimensional Pressure Sensing Mattress based on Optical Coupling between Crossing Polymer Optical Fibres", we proposed a position-sensing method based on sensing local pressures exerted on a surface, equipped with a two-dimensional (2D) structure of polymer or plastic optical fibres, and experimental results of a single crosspoint using PMMA Graded Index Plastic Optical Fibre (GI-POF) in combination with a semiconductor laser were reported [1].
In this paper, novel experimental results using standard PMMA Step Index Plastic Optical Fibre (SI-POF) [2-3] in combination with low-cost LEDs devised for lighting are presented. Because the SI-POF yields less cross-fibre signal coupling in the crosspoints, a modified construction at the crossings of the fibres has been applied. Moreover, using LEDs instead of lasers, makes the system more robust and lower-cost.
First a description of the system, followed by experimental results of a single crosspoint are given. As a proof-of-concept, a setup and a measured 2D pressure profile of a person lying on a mattress are presented. Moreover, a real-time system has been realized and described. Finally, a modified simple pressure-sensitive POF crossing construction is presented using rigid rings, which results in local fibre bending at the crossings when pressure is applied. The advantage of this solution is that the fibres can be left intact, so a 2D POF structure can be produced more easily.

2. System description

Figure 1, shows the principle of operation of the real-time 2D pressure sensing system based on monitoring the local pressure exerted per crosspoint on a 2D structure embedded in a 2D surface, such as a mattress. The system consists of a 2D sensing module, an Optoelectronics module and a Data Acquisition and Control module. The 2D sensing module is composed of a grid of SI-POFs which form a matrix of crosspoints. The so-called transmitting fibres of the POF grid are connected to LEDs and the receiving fibres to photodiodes of the Optoelectronics module. The Data Acquisition and Control module controls the LEDs and processes the measured data from the Optoelectronics module. The optical coupling between the POFs at the crosspoints is a function of the local pressure, so by detecting the optical power received by the photodiodes, the pressure on a crosspoint can be measured. Because the optical coupling effect between transmitting and receiving SI-POF fibres is very small, high-sensitivity optical receivers are needed, using transimpedance amplifiers (TIAs) with high gain and a high input impedance. Sensitivity is increased further by modulating each optical source with a low frequency carrier and applying highly-selective synchronous or lock-in detection, executed by multiplying the received amplified signal with the same carrier signal driving the LEDs and low-pass filtering the output.

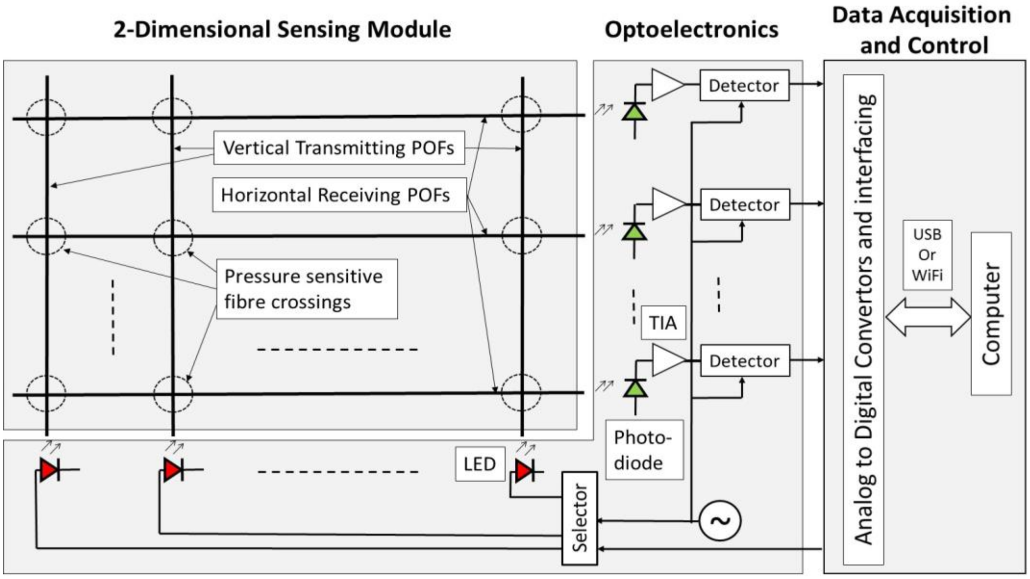

Figure 1. 2D position sensing system deploying a matrix of step index plastic optical fibre (SI-POF) crosspoints.

To achieve a simple and scalable system, a crosspoint scanning method is implemented. The Data Acquisition and Control module in figure 1 controls the Selector, which selects only one LED at a time, and the crossings are scanned column by column. Reading simultaneously the detector outputs line-by-line enables the Data Acquisition and Control module to do the 2D pressure detection. This solution is readily scalable because N photo detectors plus M LED sources can detect $N \times M$ sensor points.

3. Experiments with locally removed cladding crossings

A typical standard Step Index POF (SI-POF) consists of a core with a diameter of 0.98mm surrounded by a cladding with a diameter of 1mm and is made of a polymer, typically PMMA (poly-methyl metacrylate) which is transparent for light in the visible spectrum (400-700nm) [2-3]. The light is guided through the POF in its core, in which the light is confined by reflection at the core-cladding boundary. The refractive index of the core of a SI-POF is uniform across the whole core. A jacket or protective coating surrounds the cladding and protects the core-cladding structure against external influences.

A possible practical implementation of a single pressure sensitive SI-POF crosspoint is shown in figure 2. It is composed by two fibres crossing each other at an angle of 90 degrees. Light is injected in the transmitting fibre and guided within the core of the fibre. The jacket or protective coating of the transmitting fibre is removed locally at the crossing, see figure 2a. Moreover, a small area of the cladding of the transmitting fibre is also removed so a small percentage (< 0.1%) of the light in the core can escape. Because of this small percentage, the optical power in the transmitting fibre is nearly constant over the whole length of the fibre (which is less than a few meters). At the crossing, the jacket or protective coating of the receiving fibre is removed over a few centimetres and replaced by an elastic scattering non-absorbing primary

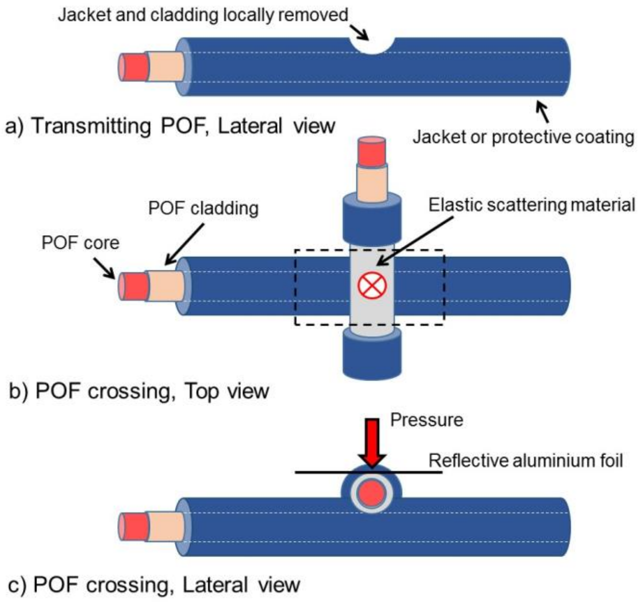

Figure 2. Pressure sensitive SI-POF crosspoint.

coating, see figure 2b, and is positioned such that the elastic scattering primary coating of the receiving fibre can make physical contact to the core/cladding of the transmitting fibre at a fixed position, see figure 2c. By applying pressure at the crossing some light of the transmitting fibre, which is coupled in the elastic scattering primary coating of the receiving fibre, may then be transmitted via the cladding into the core of that receiving fibre. In order to further enhance the coupling of light which has escaped from the transmission fibre into the receiving fibre, a reflective structure (such as a reflective aluminium foil) is added locally at the crosspoint, as shown in figure 2b and 2c. Thus in a single crosspoint which is only about 3mm thick, some light gets from the transmitting fibre into the receiving fibre. The amount of this transitioning light depends upon the force exerted onto the crosspoint.

The characteristics of a single crosspoint have been measured by loading the crosspoint with an external weight. A simple visible white light LED with an output power coupled into the SI-POF of about 3 mW is modulated with a square wave signal with a frequency of 1 kHz. At the receiver side, the current of a silicon photodiode is amplified with a transimpedance amplifier with a feedback resistor of 50 Mohm. The combination of an analog switch and a differential amplifier performs the synchronous detection operation. After low-pass filtering, the DC detector output voltage is measured with a multimeter. Figure 3 shows the measured output voltage as a function of the applied weight, without and with reflective aluminium foil. A weight of 100g can already be detected. This measured signal shows a clear and nearly linear relation to the weight pressure on the crosspoint. No significant influence of weight pressure of neighbouring crosspoints is observed.

A proof-of-principle setup has been realized to measure a 2D pressure profile of a person lying on a mattress, see figure 4, in which scanning (i.e. the switching of the receiving fibres to a single photodiode) is done by hand. The sensor grid consists of 8 transmitting and 8 receiving SI-POFs, so the grid consists of 64 crossings. The pressure profile from shoulder to hip of the person in figure 4 is clearly visible.

Next, a real-time 2D profile measurement set-up has been realised using a National Instruments MyRIO controller device [4] as the interface between optical receiver outputs and selector of the optoelectronics, see figure 1, and computer. With this MyRIO controller, 8 profiles per second can be real-time visualised on an external computer or stored on a USB stick directly connected to the MyRIO for analysis afterwards. Because of the small amount of data needed for one profile, very long time periods can be stored efficiently on a USB stick with limited capacity.

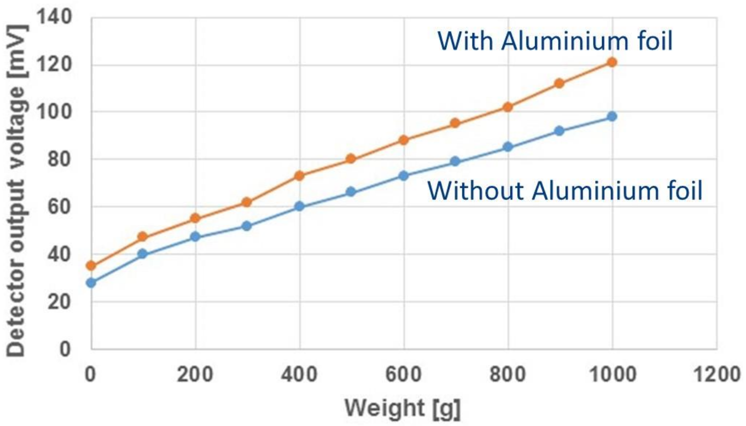

Figure 3. Detector output voltage, versus exerted pressure on the crosspoint.

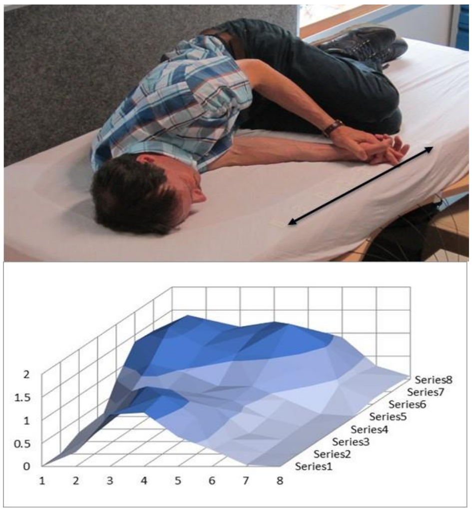

Figure 4. Pressure profile of a person lying on a mattress with an 8 x 8 POF grid underneath.

4. Experiments with bending based crossing

Bending optical fibres can introduce losses because of light that escapes [2]. Bending a waveguide with a sufficiently small bend radius, will slightly disrupt the confinement of the light in the core of a transmitting fibre so a small fraction of the light will leak through the cladding. The light that escapes can be captured in a crossing fibre. Bending enhances both light emitted from a transmitting waveguide and the ability of a receiving waveguide to couple incident light into its core. So locally bending of crossing optical fibres when pressure or force is exerted, can result in optical coupling between the two crossing fibres, which is proportional to this exerted pressure or force.

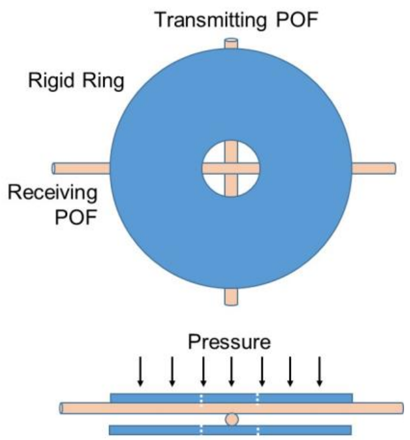

Figure 5. Crossing fibres having two rigid rings to enhance bending under pressure.

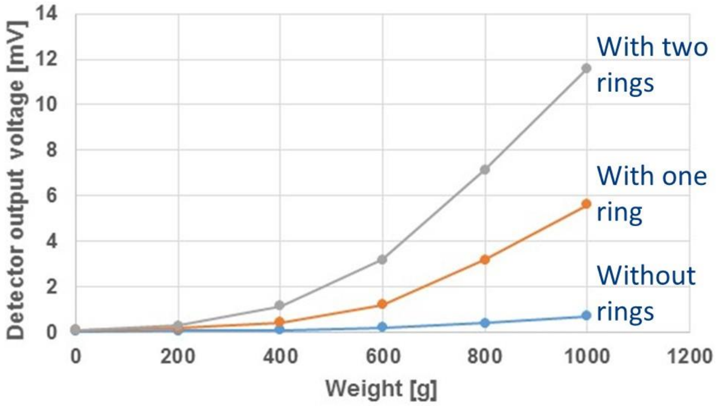

Figure 6. Detector output voltage, versus exerted pressure on the crosspoint without and with one or two rings.

Here, the application of simple rigid rings at a crossing is proposed, which realizes bending of the fibres when pressure is exerted. Figure 5 shows a top- and side-view of a POF crossing sensor having rigid rings to enhance waveguide bending under pressure. Inside the hole of the rings, the fibres will bend when pressure is applied on the rings, and optical cross coupling is mainly due to bending of the transmitting and/or receiving waveguides in this case. This construction is easy to produce, because when bare fibres are used, the fibres can be left intact and alignment is not critical. The crossing is still very robust. In figure 6 measurement results are shown, of a SI-POF fibre crossing without and with one or two rigid rings using the measurement setup described in section 3. The rings have an inside hole diameter of 8.5mm and an outside diameter of 50mm. These measurement results clearly show the enhancement of the optical coupling of the crossing POFs. Moreover, the linearity of these transfer characteristics can be improved by some signal processing done in software.

Conclusion

An optical method to perform two-dimensional location sensing, based on the pressure-sensing function realized by measuring the changes in optical characteristics of a two-dimensional structure composed of slightly deformable crosspoints made of step index plastic optical fibre has been described and experimentally verified. Because of the use of plastic optical fibre, this sensing method is robust, flexible, scalable, waterproof, is not affected by external electrical fields, nor does it generate any electrical fields itself, and is only a few mm thick so can e.g. easily be put under (or integrated inside) a mattress. The method is also low-cost because readily available optical and electrical components can be used like LEDs for lighting and silicon photodiodes, and only low-frequency components are needed. Measurements of a single crosspoint show a sensitive and nearly linear pressure detection characteristic. Two-dimensional pressure profile measurement results of a person lying on a mattress clearly show his position. Using a National Instruments MyRIO controller device, a real-time two-dimensional profile measurement setup has been realised, visualising and storing 8 pressure profiles per second. An alternative simple, robust and easy to produce POF crosspoint principle based on fibre bending is described and experimental results with rigid rings are given.

The two-dimensional pressure sensing principle based on optical coupling between crossing fibres, can be used for many other applications; for instance it can be used under (or woven into) a carpet or under a PVC floor to detect walking and falling of (elderly) persons, which is much more privacy-friendly than using video cameras.

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