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Two axis optoelectronic tactile shear stress sensor

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ABSTRACT

Tactile sensors are often used on irregular or moving surfaces, for example as artificial skin on a robotic hand or inside a prosthetic socket. In addition to tactile sensors able to detect pressure, there is also a need to detect shear stress, associated with slippage or friction. Therefore, this paper demonstrates a technology for fabricating unobtrusive flexible tactile shear sensors using a thin and mechanically strong polyimide substrate. The operation of the sensor is based on the changing optical coupling between a Vertical-Cavity Surface-Emitting Laser (VCSEL) and photodiode. Since this sensor is based on an optical principle, it is less susceptible to environmental influences and electromagnetic interference (EMI). Furthermore, a new design of this sensor was developed and tested to enable the detection of both shear force magnitude and direction (two axis sensor).

1. Introduction

Tactile sensors are gaining importance in several fields such as robotics, sports or the medical sector. The possibility of equipping robots or physically disabled people with an artificial sense of touch is probably the most appealing application. Furthermore, tactile sensors can be used to measure stresses inside a prosthetic socket or sports shoes to monitor and optimize user performance.

In several of these applications, not only pressure sensing (“normal stress”), but additionally shear stress sensing plays a significant role since this type of stress is associated with friction or slippage effects. For example, to allow a robotic hand to lift delicate objects, the amount of slippage determines the grasping force to be exerted. Similarly, the movement of a residual limb inside a prosthetic socket, e.g. during walking, causes frictional stress which needs to be limited to prevent serious skin injury.

Obviously, the required tactile sensors need to be adjusted for operating on, or in contact with the human body. Firstly, the sensor should be unobtrusive, i.e. thin, flexible and without protrusions which may irritate the skin, for example inside a prosthetic socket. Secondly, the sensor operation should not be influenced by the human body.

In literature, several types of shear sensors have been reported. Earlier, the operation of these sensors mostly relied on MEMS (Microelectromechanical Systems), fabricated using silicon micromachining techniques. A typical sensor configuration applies the piezoresistive effect in these semiconductors to detect mechanical stresses [1–3]. Such sensors can be highly linear and sensitive but the fabrication process is complicated and the used silicon substrate is inherently not flexible. Therefore, the focus is currently shifting towards polymers, which can be exploited more easily to fabricate flexible sensors. A large amount of such polymer sensors are based on the simple principle of changing capacitance [4,5], and are consequently also susceptible to electromagnetic interference (EMI) or stray capacitance. This situation is unfavorable since the sensors need to be used in proximity with the human body which acts as a stray capacitance, influencing the sensor operation.

Systems using optical sensing principles do not suffer from these negative effects and therefore a shear sensor is presented based on the changing optical coupling between a light source and a detector. Furthermore, the system can be implemented using thin and flexible layers resulting in an unobtrusive sensor which can be applied on the human skin or other irregular surfaces.

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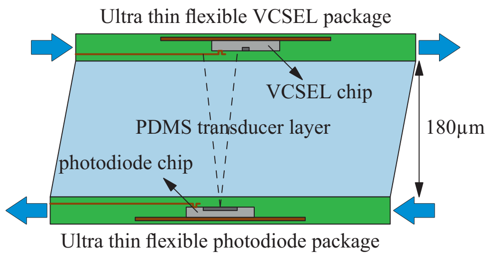

Fig. 1. Principle of the shear sensor (side view).

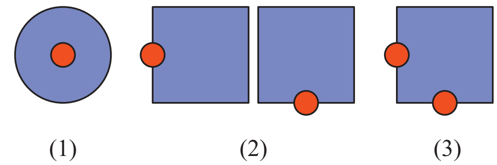

Fig. 2. Various shear sensor configurations using different photodiode shapes and different initial lateral VCSEL-to-photodiode alignment (as seen from the top). The small red circles represent the VCSELs and the blue structures represent the photodiodes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Sensor design

2.1. Principle

The principle of the sensor is based on the changing optical coupling between a Vertical-Cavity Surface-Emitting Laser (VCSEL) and a photodiode depending on their relative lateral displacement. Such a sensor is able to record displacements and can be transformed into a shear stress sensor using a transducer material, as illustrated in Fig. 1. In order to make the sensor thin and flexible, the required optoelectronic components were thinned and embedded in polymer foils of about 40 μm thickness. These foils were separated by a 180 μm thick Polydimethylsiloxane (PDMS) transducer layer (Sylgard® 184, Dow Corning) resulting in the final sensor topology.

2.2. Optical sensor architecture

The modeling of the sensor can be subdivided in two independent studies. The first study involves the photodiode current variation as a function of the relative lateral displacement of the VCSEL and photodiode ("optical response"), while the second study involves the relation between the applied shear stress and lateral displacement of the top sensor part when the bottom part is kept fixed. Using this mechanical relation, the photodiode current as a function of the applied shear force is obtained ("mechanical response").

The mechanical response depends on the dimensions and properties of the transducer layer. It was found that the mechanical behavior of this material, the relation between shear stress and lateral displacement, was linear for small displacements (experimentally verified up to 100 μm). The optical response was studied using an analytical sensor model based on simplified characteristics of the optoelectronics. Therefore, the photodiode sensitivity curve was considered to be linear, uniform and independent of the angle of incidence, which is valid since the VCSEL beam exhibits a small divergence angle (typically 3–8°, single sided). The used VCSELs are multi-transverse mode emitting (250 μm pitch 1 × 4 array, ULM Photonics [6]) but their beam profile was nevertheless considered to be Gaussian. From the experimental results it was shown that this simplification is valid when the vertical distance between VCSEL and photodiode is limited to a few hundred micrometer, since the photodiode is then averaging out any irregularities in the beam profile. The Gaussian beam is specified by the total emitted optical power and opening angle, defined as the single sided angle wherein 50% of the optical power is confined. These parameters depend on the driving current and were measured [7] to serve as an input for the analytical model. In the remainder of this paper, a VCSEL driving current of 5 mA is considered, corresponding with an opening angle of 6° and a total emitted power of about 1.7 mW.

The optical response $\Psi(x, y)$, i.e. the photodiode current as a function of the lateral (x, y) position of the VCSEL relative to the photodiode can be calculated as a convolution of a two-dimensional function representing the photodiode, $PD(x, y)$, and another function representing the VCSEL beam, $\Phi_d(x, y)$:

$$\Psi(x, y) = (\Phi_d * PD)(x, y) = \int\int \Phi_d(x', y')PD(x - x', y - y')dx'dy'$$

The photodiode function $PD(x, y)$ evaluates in either a constant value or 0, for every (x, y) respectively inside or outside the photosensitive area. The VCSEL beam function $\Phi_d(x, y)$ is a two-dimensional Gaussian function, representing the intensity distribution in the beam, considered at a specific distance d from the emitting surface. Since the VCSEL beam is diverging, $\Phi_d(x, y)$ represents a broader function for larger values of d (comparable to a Gaussian distribution with a large variance) and a narrow function for small values of d (comparable to a Gaussian distribution with a small variance).

Evaluating this equation for every possible relative lateral position (x, y) of the VCSEL yields the general, two-dimensional response $\Psi(x, y)$. However, typically only the response corresponding with a displacement in a certain direction is needed, which can be obtained by evaluating along a specific line, e.g. the x-axis, resulting in the x-directional response $\Psi_x(x) = \Psi(x, 0)$. Furthermore, $\Psi(0, 0)$ or $\Psi_x(0)$ represents the sensor response when idle (no shear force applied) and hence corresponds to the optical power incident to the photodiode for the initial lateral VCSEL-to-photodiode alignment. If this mutual initial lateral alignment is changed with a certain amount, the sensor response curve is shifted with the same amount.

The VCSEL and photodiode are also vertically separated by a certain distance d, see Fig. 1. This optimum vertical VCSEL-to-photodiode separation d was previously determined to be 200 μm [8]. Since both the photodiode and VCSEL chip are covered with a protective polymer layer (see Fig. 1 and Section 3.), this separation distance corresponds with a transducer layer thickness of 180 μm. Additionally, in [9], it was simulated that normal forces have a very limited influence on the sensor response to shear force.

In [8], a first generation flexible shear sensor was proposed illustrating the optoelectronics integration technology. However, this sensor was constructed using a VCSEL initially centered above a 100 μm diameter circular photodiode (see Fig. 2, configuration 1) and therefore only the total displacement or shear force magnitude can be resolved. Due to the symmetric configuration, it is not possible to distinguish the direction in which the VCSEL is displaced. This can also directly be deduced from the calculated two-dimensional sensor response $\Psi(x, y)$, plotted in Fig. 3: when the VCSEL is moving away from its initial position (0, 0), the photodiode signal decreases, but the direction of displacement cannot be determined.

To obtain the desired two axis sensor which is able to record both magnitude and direction of displacement, the sensor response $\Psi(x, y)$ needs to be modified. This can be achieved by changing either the VCSEL beam profile $\Phi_d(x, y)$, or the photodiode function $PD(x, y)$. The VCSEL beam profile cannot easily be changed unless a special filter, lenses or a different light source is used. However, the photodiode function can easily be changed by adapting the