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Photonic Incremental Pressure Sensor Based on Optical Feedback in a Polymer Embedded VCSEL

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Abstract—A highly accurate integrated incremental pressure sensor is presented based on optical feedback in a vertical-cavity surface-emitting laser (VCSEL). This laser chip is embedded in a polymer host material and an external cavity, consisting of a compressible transducer material and a reflecting layer, is fabricated on top. The reflecting layer is coupling part of the emitted laser light back into the internal VCSEL cavity causing self-mixing interferometry. By applying pressure and consequently changing the external cavity length, this interference signal adopts a periodic shape corresponding to half the VCSEL wavelength. The use of unpackaged VCSELs limits the sensor dimensions and minimizes the distance between two adjacent sensing points. A proof-of-principle setup is developed and the integrated sensing principle has been demonstrated using a polydimethylsiloxane transducer layer. A 850-nm VCSEL is used and forces up to 300 mN are applied resulting in a 2-mV peak-to-peak variation of the electrical driving voltage.

Index Terms—Integration, optical feedback, polymer embedding, pressure sensing, self-mixing interferometry, tactile sensing, vertical-cavity surface-emitting laser (VCSEL).

I. INTRODUCTION

PRESSURE sensors are becoming increasingly important in different areas, such as the automotive industry, the structural health sector and biomedical engineering. These markets are demanding for technologies which allow to miniaturize sensors and, at the same time, to integrate sensor elements with microelectronic functions in minimal space. Within the medical application domain additional requirements apply such as biocompatibility, mechanical flexibility and sensor insensitivity to electro-magnetic interference.

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Fig. 1. Schematic overview of the VCSEL sensor principle.

The existing microelectromechanical systems (MEMS) pressure sensors are mostly based on piezoresistive or capacitive force sensing technologies [1]. Optical alternatives, mostly based on fiber sensors, have been developed by several institutes [2]. These sensors can perform absolute pressure measurements and offer unique advantages such as immunity to electromagnetic interference and capability of operating in harsh environments. We present an optical, incremental, VCSEL-based sensor based on self-mixing interferometry in an external laser cavity. Using unpackaged laser chips, one can embed this sensor element in an ultra-thin flexible package (an optical sensing foil) which can be mounted on a non-planar surface or even irregularly shaped objects, such as the human body.

II. PRINCIPLE OF OPERATION

The pressure sensing mechanism is based on the self-mixing interference effect in VCSELs which is observed when a fraction of light emitted from the laser is injected back into the laser cavity by reflection from an external target on a distance L_{external} from the VCSEL emitting area [3]. As a result, an external cavity is created between the VCSEL and the external reflector (Fig. 1). Due to the coherence of the emitted laser light, the recoupled light mixes in a deterministic way with the light in the internal laser cavity. The phase shift introduced by the round trip travel to and from the target, influences the optoelectronic characteristics of the laser. Increasing or decreasing L_{external} results in a periodic variation of laser wavelength, optical power and electrical resistance, all with period $\lambda/2$ (λ being the emitting wavelength of the VCSEL, in this letter 850 nm). This means that the target displacement can be calculated by monitoring the periodic signal between

Fig. 2. Discrete setup: (a) position of the moveable reflector, which was mounted on a microstage (reference versus experiment), and (b) variations in the electrical current (reference versus experiment). The driving voltage was kept constant at 1.6 V.

the initial and the final position of the target, where the spacing between the two consecutive peaks corresponds to the distance of $\lambda/2$. Similar interferometric effects in VCSELs can be used to sense other parameters or even perform multi-parametric sensing [4].

The conversion of external pressure into displacement is guaranteed by the use of a compressible polydimethylsiloxane (PDMS) layer as an external cavity which is applied on top of an ultra-thin flexible VCSEL package (Fig. 1). The sensitivity of the pressure sensor is defined by the mechanical properties of this external cavity transducer material.

A discrete setup was developed to mimic the principle of this new integrated sensing mechanism: an unpackaged wirebonded VCSEL was put on a fixed location and a moveable reflector was positioned close to the active area. This moveable reflector consisted of a coating layer of evaporated gold on top of a multimode silica fiber with a $62.5 \mu\text{m}$ core diameter. The external cavity consequently consisted of an air gap between the light emitting area of the VCSEL and the moveable reflector. Moving the reflector 4 times over $5 \mu\text{m}$ (Fig. 2, top) results in a periodic variation of both the monitored optical power and electrical VCSEL driving current (Fig. 2, bottom) while the VCSEL voltage is kept constant at 1.6 V. A Keithley 2400 Source Measurement Unit is used to control the VCSEL junction voltage and read out the VCSEL driving current. A total of 47 periods can be observed in Fig. 2 bottom, demonstrating the 425 nm periodicity.

III. METHODS

A. Fabrication

The proposed optical pressure sensor consists of a flexible optoelectronic package (an ultra-thin flexible VCSEL package), a deformable PDMS layer acting as an external cavity and a reflecting top layer providing optical feedback, as illustrated in Fig. 1. To fabricate a flexible and ultra-thin package, the 850 nm GaAs VCSEL die (1×4 array, $250 \mu\text{m}$

Fig. 3. Microscope view of a force applying unit of top of the integrated pressure sensor (reflecting layer not shown).

pitch, ULM Photonics) was thinned down to $20 \mu\text{m}$ and embedded in a flexible polymer package of $40 \mu\text{m}$ thick using a dedicated integration process which was extensively optimized and characterized [5].

This VCSEL package was fabricated on a temporary glass substrate and on the VCSEL package a $50 \mu\text{m}$ thick PDMS layer, Sylgard 184[®] from Dow Corning, was spin-coated (Fig. 1, package A). To enhance the mechanical robustness, the reflecting copper layer was sputtered on a non-functional flexible package. After patterning the metal layer, a $50 \mu\text{m}$ thick PDMS layer, Sylgard 184[®] was spin-coated on top (Fig. 1, package B). Finally, both the VCSEL and mirror package were released from the glass substrate and the PDMS layers were treated with an air plasma (Diener Pico, 0.8 mbar, 24 s, 190 W, 40 kHz generator). After aligning the reflecting layers with the VCSEL active areas, both packages were brought into contact, creating an irreversible bond and a total transducer layer thickness of $100 \mu\text{m}$. A similar approach can be used to create other types of sensors measuring other parameters such as shear force [6].

B. Characterization of the Sensor

The pressure sensor was mechanically characterized by applying a controlled displacement and simultaneously reading out the corresponding force. During sensing operation, the VCSEL driving current was held constant and the VCSEL voltage was read out. Monitoring the optical power and wavelength changes requires additional read-out equipment effacing the integration advantages and is therefore avoided. An example of a characterization setup is depicted in Fig. 3 (for illustration purposes only, the integrated reflecting layer is not shown). Characterization tests were performed using a nano-indenter setup with spherical indentation tips.

IV. RESULTS AND DISCUSSION

Embedded VCSEL arrays were subjected to a linear displacement variation. The spherical indentation tip ($10 \mu\text{m}$ radius) was actively aligned on top of the VCSEL light emitting area. The applied displacement and corresponding measured force values are shown in Fig. 4. Variations in the electrical VCSEL junction voltage were monitored through a Keithley 2400 Source Measurement Unit (Fig. 5). Roughly 22 periods are visible in the time-domain signal and given that

Fig. 4. Linear displacement and corresponding force applied on the integrated pressure sensor.

Fig. 5. Measuring the electrical voltage variation (2-mV peak-to-peak) while keeping the driving current constant at 1 mA during a 10- μm indentation.

Fig. 6. Result of frequency analysis performed on the measured VCSEL voltage variation.

1 period corresponds to a change in external cavity length of 425 nm, an experimentally measured displacement of 9.4 μm is obtained. The difference between the actual displacement and the experimentally measured value can be explained by a 0.6 μm compression of the polymer embedding layers, including the mirror package with the reflecting layer. This effect becomes more important for higher force values. Signal processing, including a lowpass 3th order Butterworth filter and a fast fourier transform to determine the spatial frequency of the signal, yields a peak frequency in the power spectrum at 2.27 μm^{-1} (Fig. 6). This spatial peak frequency corresponds to a reciprocal interferometric signal period of 881 nm, slightly higher than the expected 850 nm value. The sensor integration process consequently introduces an error of 5%.

From Fig. 5, a 2 mV peak-to-peak signal variation can be determined. This yields a displacement responsivity of 4.71 $\frac{\mu\text{V}}{\text{nm}}$. Through the Sylgard 184[®] Young's modulus, a pressure reponsivity of 26.2 $\frac{\mu\text{V}}{\text{mbar}}$ is obtained.

The spatial responsivity of the sensor was checked by scanning an indentation matrix of 7 $\times$ 7 sensing points on

Fig. 7. Measuring the spatial dependency of the VCSEL sensor. (a) Top view of the VCSEL array chip with schematic representation of the indentation matrix. (b) Frequency analysis performed on each indentation point.

a total area of 240 $\times$ 240 μm^2 on the VCSEL emitting area (Fig. 7, left) and using an indentation sphere with a radius of 150 μm and forces up to 300 mN. The driving current was kept constant at 1 mA, the electrical voltage variations were monitored and frequency analysis was performed as described above. The resulting spatial peak frequencies are shown in Fig. 7, right (linearly interpolated between the 49 measuring points) and a peak frequency of 2.52 μm^{-1} is obtained on top of the light emitting area. The sensor responsivity has dropped to 50 % at 200 μm from the central area.

V. CONCLUSION

A new pressure sensor was developed based on optical feedback in an embedded Vertical-Cavity Surface-Emitting laser. To introduce this feedback, an external cavity of 100 μm is created on top of the light emitting area. By compressing this cavity and thus changing the external cavity length, the optical and electrical VCSEL parameters are modulated. The sensing mechanism was first proven using a discrete setup and an integrated sample was subsequently characterized using a nano-indenter. A sensing displacement resolution of 425 nm was achieved and the responsivity to forces up to 300 mN in a 240 $\times$ 240 μm^2 matrix was measured. More advanced signal reconstruction techniques can enhance the sensor read-out accuracy. By choosing the appropriate transducer material, a wide range of tactile sensing applications can be targeted with this sensor.

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