Micro opto mechanical pressure sensor design: Developing a gentler brain analysis neural probe

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The human brain coordinates our perceptions, thoughts, and actions from the activity of its neurons. Neuroscientists are endeavoring to understand how the brain functions by employing methods capable of isolating, identifying and manipulating neurons at single-neuron and single-spike resolution during behavior. Neural probes have been successful in extracellular recording, brain-machine interface (BMI), and deep brain stimulation (DBS), but also in some new applications such as brain mapping, restoration of neuronal functions, and investigation of brain disorders. Ideally, a neural probe array should have good biocompatibility, high-density electrodes with a high signal-to-noise ratio, interconnection capability via flexible cables, a highly integrated electronics architecture, as well as integrated micro-actuators to drive the electrode shank in order to enable tracking of neuron movement.

In order to allow for large scale recording of a single neuron in multiple areas of the brain, a high density and large number of electrodes are needed in neural probes. Unfortunately, the latest high-density CMOS neural probes have a large ‘shank’, which is the part of the probe that gets implanted into the brain area. This ‘shank’ portion needs to be as thin as possible so as to not disturb or damage normal brain function; right now, they are not as small as neuroscientists would like. In addition, the present electronic design architecture is not optimal. The probe design consists of a large number of small active electrodes that amplify and buffer neural signals. The CMOS pixel amplifiers (PAs) are under the electrodes in a very tiny space; the signal processing is forced to be handled at the Base of the probe due to lack of space. Imagine the noise problems in this non-ideal routing of signals that ideally want the signal processing right next to the PA.

[See: imec MEMS-based Neural Probe: Striving for less invasive brain monitoring]

The MOM pressure sensor

Let’s start with pressure sensor design. There are MEMS pressure sensors, which are capacitive and piezo-based, which are small and have pretty good performance. There are also optical fiber sensors, which have characteristics of hypersensitivity and low noise, but are optimal in a less integrated design architecture.

Now, let’s combine both of the above sensor characteristics into one integrated sensor known as a micro opto mechanical (MOM) pressure sensor. This device brings us an increased sensitivity and an improved noise characteristic as compared to piezoelectric and capacitive sensor designs, but in the same footprint.
The MOM devices are demonstrated with Mach-Zehnder Interferometer (MZI) systems or ring resonators (Figure 1).

![Diagram of an unbalanced Mach Zehnder Interferometer layout with grating couplers, multimode interferometer (MMI) splitters, and a spiral waveguide arm.](Image courtesy of Reference 2)

**Figure 1** An unbalanced Mach Zehnder Interferometer layout with grating couplers, multimode interferometer (MMI) splitters, and a spiral waveguide arm (Image courtesy of Reference 2)

A typical MZI MOM Pressure Sensor, seen in Figure 1, is composed of a MMI splitter, two waveguide arms and an MMI combiner as shown in Figure 1. The design takes one of the MZI arms and puts it on a flexible membrane (Figure 2) that is subjected to a differential pressure; the other MZI arm serves as a fixed reference. There is a compromise determined at design regarding the number of loops in the spiral: Increasing the number of loops decreases the pressure range while increasing the sensitivity and vice-versa.

In functionality, the optical intensity emanating from the MZI is dependent upon the phase difference between the arms and the differential pressure to which it is subjected. The MZI is ‘unbalanced’ because one of the arms is much longer than the other.

In the process of fabricating this device, a sensing membrane is created. When this membrane deflects, the position of the waveguide changes and in turn induces an optical path elongation that causes a phase shift in that particular arm (Figure 2).

![Cross section of the membrane](Image of cross-section showing deflection)

**Figure 2** In this micro-optical pressure sensor cross-section, the lower view shows deflection under
Spectral bandwidth is a critical parameter that greatly affects the sensitivity of the laser. The implementation of a balanced MZI will take care of this effect.

The laser output will have noise due to quantum noise and laser cavity variations. The two types of significant noise are intensity noise and wavelength drift. Intensity noise can be corrected by adding a power tap that will subtract the noise directly from the signal. Wavelength drift is reduced by adding a filter, like a ring resonator, at the circuit input.

The modified design

The modified design of the MOM pressure sensor now has a balanced MZI; the first is a single loop for large range measurement and the second divides the signal of the sensitive spiral into two de-phased outputs so that we will always have a sensitive measurement for each pressure (Figure 3).

The neural probe

A good active neural probe buffers/amplifies the input signal as close to the source/electrode as possible in order to enhance the signal for best recording quality. This method will reduce the source impedance and minimize crosstalk from coupling effects of lengthy shank wires nearby.

The area of the PA is limited by the size of the electrodes. Its power is limited by an acceptable tissue heating limit. Noise requirements need to be low as compared to the smallest signal amplitude which can be at the level of tens of microvolts. An easy way to reduce noise is usually to supply more current to the PA transistor; this will also enable a higher a higher bandwidth.

The neural probe has a signal bandwidth of about 7.5 kHz and the PA output can be sampled at 15 kHz. The designers saw that time division multiplexing technique could be embedded into the shank (Figure 4a). This would allow M number of PA outputs on each unique shank wire. Without an anti-aliasing filter to limit the PA bandwidth will make the in-band noise due to folding. It was not possible to fit lowpass filters into the small PA area at the point before the sampling takes place. Designers chose to use an architecture which would integrate the signal over a time period of $T$, \[ T = \frac{1}{f_s} \]
Figure 4b) to attenuate the signal beyond the sampling frequency, \( f_s \), which would improve the signal-to-noise ratio (SNR).

Figure 4

4a shows what happens when the circuit is multiplexing without a filter; 4b shows that the filtering of the signal by integration lowers the out-of-band noise level. (Image courtesy of Reference 2)

The signal flow in the probe architectural design (Figure 5) flows from the output of an array of eight multiplexed PAs to the Base through a shared shank wire. The signal then goes into an integrator in the Base of the probe and the output of the integrator is demultiplexed via eight sample-and-hold circuits designated \( V_o<x> \). Next each of the eight individual \( V_o \) goes into its own channel block in which the signals are amplified and filtered so that the output is only the band of interest. All of the 20 channels are next multiplexed and digitized into a 10-bit Successive approximation register (SAR) A to D converter (ADC) and sent to the digital control block which supplies the ADC and MUX/DEMUX clocks and it is here that all the ADC’s parallel outputs become serialized into just six data lines.

Figure 5

The probe architectural design and signal flow has a pseudo-differential signal path from input to output. (Image courtesy of Reference 2)
The pixel amplifier (PA)

The designers were very creative in their PA architecture which is split into two areas. The PA is essentially a voltage-to-current converter (Figure 6).

Figure 6 shows that the current out of the voltage-to-current converter gets integrated for 2.5 us across capacitor $C_i$ and then gets sampled and moved on the de-multiplexer. More details of the signal chain may be found in Reference 2.

Ultimately, the outcome of this design architecture resulted in a minimum of a $2\times$ increase in the number of simultaneous recording channels as compared to the existing state-of-the-art probes out there today.

I fully anticipate many more architectural advances in this electronics space in the coming days. Medical electronics will greatly benefit from MEMS and sensors and other architectural advances, along with semiconductor innovations, to help improve the lives of people with medical conditions and those in the health and fitness area as well. Let’s make the world a better, healthier place with engineering technology.

References


Steve Taranovich is a senior technical editor at EDN with 45 years of experience in the electronics industry.

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