A holographic sense of smell

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A monolithic prism interferometer achieves odor sensing with high sensitivity at high speed and low cost.

Odor sensing in an uncontrolled environment is an imposing problem whatever technology is applied. In controlled environments some chemical sensing technologies show impressive detection abilities for substances such as nerve gas, explosives constituents, and solvents. Yet there is no general-purpose technology able to discriminatively identify every airborne substance needed, for example, to protect human life in an open stadium.

‘Artificial noses’ complement other analytical techniques by using a collection of selective materials, each of which transforms a material’s chemical signature into a physical change, such as in mass, resistance, or refractive index. One challenge is to devise a means of reading out these changes in a way that is highly sensitive, responds quickly, and minimizes the cost of the expendable transducer replacement. We use dynamic (i.e., real-time) holography for parallel interrogation of an optical transducer array with interferometric precision and high speed. This enables a new ‘sniff-locked loop’ method for precisely comparing two odors.

The objective is to spatially process the response of a nine-element array of polymers, shown in Figure 1(a), to determine the solvent content of a test vapor. The holography is carried out in a novelty filter configuration, using the photorefractive crystal barium titanate (BaTiO₃): the novelty filter passes only what is new in an image, thus providing sensitivity to changes in the ambient environment. Upon sudden exposure to ethanol, ethanol-sensitive elements produce an ‘odor image,’ as shown in the video frame of Figure 1(b). If the ethanol concentration remains constant after that, the signals will fade.

The novelty filter mitigates the deleterious effects of environmental noise. It also enables a sniff-locked loop detection method wherein the system input rapidly alternates (at 5Hz) between a reference and test sample for synchronous comparative detection. This method is arguably the best means of sensing small changes in a large background signal, such as might be found in a processing plant.

Small size and monolithic construction are key to attaining high precision from a fieldable interferometer. Figure 2 schematically shows our prism interferometer, which is about the size of the tip of an adult thumb. A laser beam incident on the prism is split into a signal and reference beam. The transducer (array) is deposited on a glass slide, which is fixed to the prism with a layer of index-matching fluid. The two beams intersect and write a dynamic grating in a BaTiO₃ crystal mounted directly on the prism. Precision odor detection is accomplished using both output beams.

Figure 1. Polymer array image (a) and optical response to ethanol (b).

Figure 2. In the prism interferometer a diffraction grating (DG) acts as a beamsplitter, while its transverse modulation phase modulates the diffracted beam. The polymer transducer converts chemical information to optical phase through total internal reflection, after which both signals are amplitude demodulated in the BaTiO₃ photorefractive crystal. PZT: Piezoelectric transducer. PIN: P-intrinsic-N photodiode. BaTiO₃: Barium titanate.
Figure 3. Interferometer system with 5Hz vapor generator or calibration signal. Cascaded synchronous demodulation improves sensitivity and reduces optical and electronic noise contributions, while the notch improves dynamic range by suppressing the second harmonic response. DAQ: Digital acquisition system.

The prism geometry is designed to minimize interferometer sensitivity to laser wavelength variations. To mitigate other sources of optical and electronic noise, the relative phase between the beams is modulated at 40kHz using a piezoelectric-driven grating modulator. Figure 3 presents a schematic view of the prototype system, shown in Figure 4, including the vapor modulating valve. The prism system exhibits an equivalent displacement sensitivity of about 200fm/√Hz, i.e., a signal-to-noise ratio of unity in 1s for a displacement of about 1/5000 the size of an atom. Displacement sensitivity translates into substance sensitivity depending on the transducer materials. One benchmark uses poly(N-vinyl pyrrolidone) as an ethanol sensor. Our 3σ limit of detection (LOD) of 6ppm (parts per million) in a 5s measurement time compares favorably with the microcantilever system reporting an LOD of 8ppm in 40s, and the surface-acoustic wave system with an LOD of 0.23ppm in 5min. The latter improves LOD with longer integration time.

With sensitivity comparable to other artificial nose technologies, our optical interferometer provides fast response and an ability to directly compare two odors or detect small changes in a complex odor environment. Dynamic holography tolerates imperfect optical surfaces. For this reason, transducer array production does not require great precision and can be low cost. Because the entire array sits on a single glass element, it is easily exchanged in the field to accommodate the odor-sensing problem at hand.

Figure 4. Prototype system with laser (right), prism interferometer (center), and valve (left).

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References