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Transduction between Magnets and Ions

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Conceptual insights

Signal transduction is central to Internet of things. In particular, human-machine interfaces have been developed to transduce signals between ions and electrons. Hydrogel, a polymer network that hosts a large amount of water and mobile ions, is an ideal bridging material for human-machine interfaces. Here we develop signal transduction between magnets and ions—magnetoionic transduction. When an electromagnetic coil generates a time-varying magnetic field near a hydrogel, ions move in the hydrogel and an open-circuit voltage is measured between the two ends of the hydrogel. An ionotronic transformer is designed to achieve noncontact signal transduction between electrons and ions. The softness of the ionotronic transformer may extend the application scope of transformers to new domains, such as wearable motion detectors. One can also imagine real-time, wireless, and tissue-attachable arrays of receivers and transmitters for signal transduction—a ubiquitous connectivity between life and machine.

Transduction between Magnets and Ions

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Abstract

A time-varying magnetic field generates an electric field in an electrolyte, in which ions move. This magnetoionic transduction is studied here in several arrangements. The electrolyte is a hydrogel containing mobile ions, and is in contact with two metallic electrodes. An alternating electric current applied to a metal coil generates a time-varying magnetic field. In response, ions in the hydrogel move. The two hydrogel/electrode interfaces are non-Faradaic and accumulate excess ions of opposite signs, which attract and repel electrons in the two electrodes. When the two electrodes are connected to a voltmeter of internal resistance much larger than that of the hydrogel, an open-circuit voltage is measured, linear in the alternating current applied to the metal coil. A metal coil and a hydrogel coil form an ionotronic transformer, in which an alternating electric current in the metal coil induces an alternating ionic current in the hydrogel coil. Such a transformer can be used for noncontact power transmission, with a voltage high enough to turn on many light-emitting diodes in series. The hydrogel is soft, and readily conforms to a curved surface, such as a glove on a human hand. Motion of the hand can be detected by noncontact magnetoionic transduction.

Introduction

The Internet is connecting everybody and everything to generate data, learn from them, and create values. Examples include sensors for healthcare,[1–3] structural health monitoring,[4] and autonomous vehicles.[5] Central to ubiquitous connectivity is physical means of signal transduction. For instance, electrophysiology has re-emerged as an active field of development, called bioelectronics.[6–8] Specifically, human-machine interfaces transduce ionic signals in bodies and electric signals in computers, bidirectional, for neural recording and stimulation. [9–17]

Here we describe a method of one-directional signal transduction from magnets to ions (Fig. 1). To fix the idea, consider a hydrogel, a polymer network that hosts a large amount of water, in which ions are mobile. We terminate a line of hydrogel by two metallic electrodes, and monitor their open-circuit voltage. The hydrogel/electrode interfaces are assumed to be non-Faradaic: ions in the hydrogel and electrons in the electrodes do not combine by electrochemical reaction. Each interface functions as a capacitor. In the absence of any external field, the voltmeter records a static voltage, depending on the electrodes, hydrogel, ions, and initial preparation of the circuit. When we apply a time-varying magnetic field near the hydrogel, an electric field is generated, which moves the ions in the hydrogel. Because the two hydrogel/electrode interfaces are non-Faradaic, ions of opposite signs surge at the two interfaces. An open-circuit voltage is measured between the electrodes when the voltmeter has a much larger internal resistance than the hydrogel.

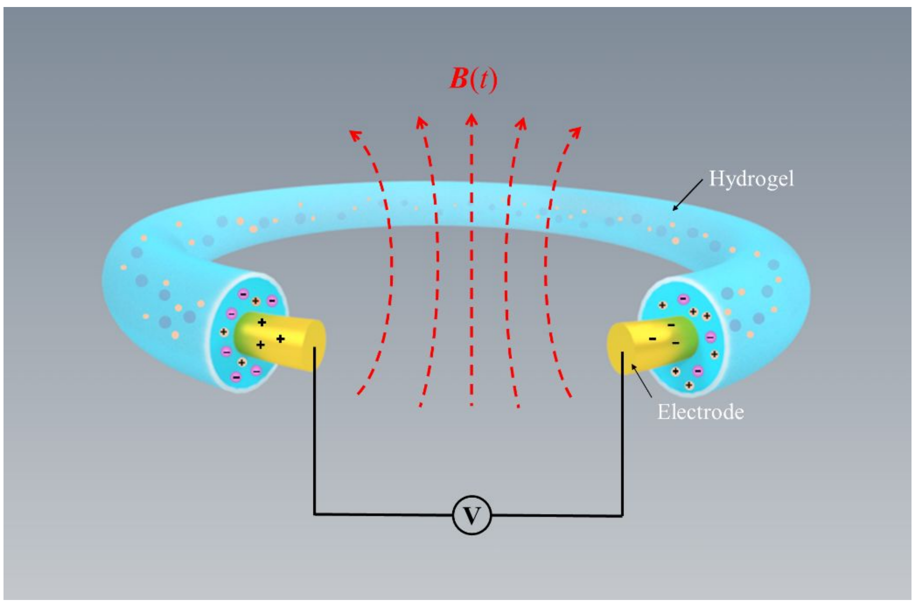

Fig. 1 Principle of magnetoionic transduction. A line of hydrogel is terminated by two metallic electrodes, which are connected to a voltmeter. The hydrogel is insulated in a tube of dielectric elastomer. A time-varying magnetic field $\boldsymbol{B}(t)$ generates an electric field, which causes ions in the hydrogel to move. Ions of opposite signs surge at the two interfaces between the hydrogel and the electrodes. The voltmeter records an open-circuit voltage.

We study this magnetoionic transduction under the time-varying magnetic field generated by an electromagnetic coil. We show that the generated voltage is independent of the concentration of ions in the hydrogel, and is linear in the electric current applied to the electromagnetic coil. Magnetoionic transduction enables noncontact transduction between electrons and ions. As an illustration, we use a metal coil and a hydrogel coil to form an ionotronic transformer, and use it to turn on many light-emitting diodes in series. Furthermore, we show that the magnetoionic transduction can be used as for noncontact motion detection.

Results and Discussion

Voltage Generated by an Electromagnetic Coil

Faraday's law states that

$$U = -\frac{\partial}{\partial t}\iint \mathrm{d}\boldsymbol{A} \cdot \boldsymbol{B}(\boldsymbol{r}, t). \tag{1}$$

The integration is over the area of a surface bounded by a closed curve. Here $\boldsymbol{B}(\boldsymbol{r}, t)$ is the magnetic field as a function of position $\boldsymbol{r}$ and time t, $\mathrm{d}\boldsymbol{A}$ is an infinitesimal area of the surface, and U is the voltage generated by the magnetic field. Consider a line of hydrogel terminated by two metallic electrodes, which are connected to an oscilloscope (Fig. 2a). The hydrogel is in an acrylic mold, which is placed on top of a metal coil. When an electric current is applied to the metal coil, according to Ampere's law, a magnetic field is generated. A voltage is measured between the electrodes at the two ends of the hydrogel. Unless otherwise specified, the hydrogel is polyacrylamide (PAAm) hydrogel containing 2 mol/L NaCl. Mechanical properties of the PAAm hydrogel have been studied and characterized.[18-20] In particular, Young's modulus is on the order of 10 kPa. The hydrogel can be stretched elastically several times its original length. In the experiment, a sinusoidal current, amplitude 150 A and frequency 162 kHz, is applied to the metal coil. The hydrogel is made long, so that the magnetic field near the electrodes is negligible.

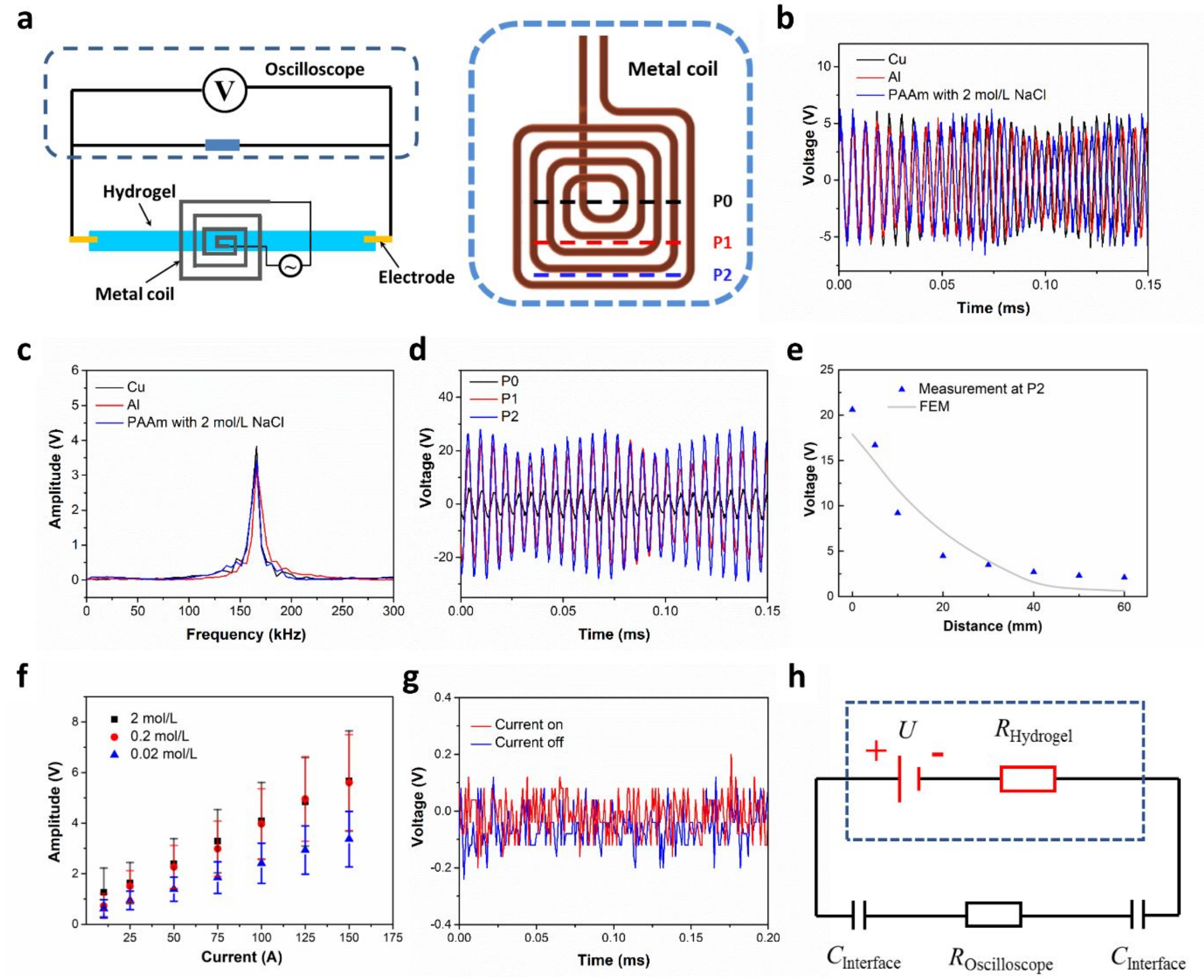

Fig. 2 An electromagnetic coil generates a voltage between the electrodes at the two ends of a hydrogel. a, Experimental setup. A line of hydrogel is terminated by two metallic electrodes, which are connected to an oscilloscope. When a sinusoidal current, amplitude 150 A and frequency 162 kHz, is applied to a metal coil, a time-varying magnetic field is generated, which in turn generates a voltage between the electrodes. Unless otherwise specified, the hydrogel is polyacrylamide hydrogel containing 2 mol/L NaCl. **b,** The voltage generated between the two ends of the hydrogel is recorded as a function of time. Also measured are the voltages generated between the two ends of a copper or aluminum line. The hydrogel line and the metallic lines have the same geometry and are placed at the same position, P0. As a result, the measured voltages are identical. **c,** The central frequency of the generated voltages between the two ends of the hydrogel line and the metallic lines is 162 kHz, which is identical to that of the applied electric current. **d,** The magnetic field depends on the position, so that the voltage generated between the two ends of the hydrogel varies with the position. **e,** The voltage generated between the two ends of the hydrogel depends on the distance between the metal coil and the hydrogel. The hydrogel line is placed at P2. Also plotted are the voltages predicted by the finite element method. **f,** The voltage generated between the two ends of the hydrogel is linear in the current applied to the metal coil. The hydrogels with three concentrations of NaCl are tested. Each data point represents the mean and standard deviation (n=3). **g,** An electromagnetic coil generates negligible voltage between the two ends of an acrylic sheet. **h,** An electric circuit model of the hydrogel, the electrodes at its two ends, and the oscilloscope.

The voltage generated between the electrodes at the two ends of a hydrogel is recorded as a function of time (Fig. 2b). The measured voltage is modulated by a low frequency signal applied to the metal coil. We have also replaced the hydrogel line with a copper or aluminum line, and recorded the voltage between two ends of the metallic line. The hydrogel line and the metallic lines have the same geometry and are placed at the same position, P0. As a result, the measured voltage between the two ends of the hydrogel is nearly identical to that between the two ends of the copper or aluminum. The central frequency of the measured voltage is 162 kHz, which is identical to the frequency of the current applied to the metal coil (Fig. 2c). We place the hydrogel on top of the metal coil at various positions, and the measured voltage varies with the positions (Fig. 2d). Moreover, we measure the voltage generated between the two ends of the hydrogel as a function of distance between the metal coil and the hydrogel (Fig. 2e). The hydrogel line is placed at P2. As the distance increases, the measured voltage between the two ends of the hydrogel decreases. Further, we calculate the spatial distribution of the generated magnetic field around the metal coil (Fig. S2). The measured results have similar trends as those calculated using the finite element method. We also measure the voltage generated between the two ends of the hydrogel containing different concentrations of ions (Fig. 2f). The amplitude of voltage is taken to be the value at the frequency of 162 kHz. For each concentration of ions, the generated voltage is linear in the current applied to the metal coil. The measured voltage is comparable for the hydrogels containing 2 mol/L and 0.2 mol/L NaCl, but is lower for the hydrogel containing 0.02 mol/L NaCl. We also place an acrylic sheet (a dielectric) on top of the metal coil, and negligible voltage is measured between the two ends of the acrylic sheet (Fig. 2g).

These observations are understood by comparing the resistance of a hydrogel to that of the oscilloscope. We develop an electric circuit model (Fig. 2h). We model the hydrogel as a power source with an output voltage U and an internal resistance R_{Hydrogel}, each hydrogel/electrode interface as a capacitor, $C_{\mathrm{Interface}}$, and the oscilloscope as a resistor, $R_{\mathrm{Oscilloscope}}$. These components are in series in the circuit, so that the amplitude of the total impedance is

$$|Z| = \sqrt{(R_{\mathrm{Hydrogel}} + R_{\mathrm{Instrument}})^2 + \left(\frac{1}{\pi f C_{\mathrm{Interface}}}\right)^2}, \quad (2)$$

where f is the frequency. As the hydrogels containing 2 mol/L and 0.2 mol/L NaCl have much lower resistances than the oscilloscope, the measured voltage is identical to the generated voltage. By contrast, the resistance of the hydrogel containing 0.02 mol/L NaCl is comparable to the internal resistance of the oscilloscope, 1 MΩ, so that the measured voltage is approximately half of the generated voltage. As a result, the generated voltage is independent of the concentration of ions in the hydrogel. For the acrylic sheet, its resistance is much larger than the internal resistance of the oscilloscope. Consequently, the measured voltage is negligible.

Ionotronic Transformer

We design an ionotronic transformer by using a metal coil and a co-axial hydrogel coil (Fig. 3a). An alternating electric current is applied to the metal coil and an alternating ionic current is induced in the hydrogel coil. To characterize the ionotronic transformer, we apply a sinusoidal electric current, frequency 500 Hz, to the metal coil, and measure the voltage induced between the two ends of the hydrogel coil.

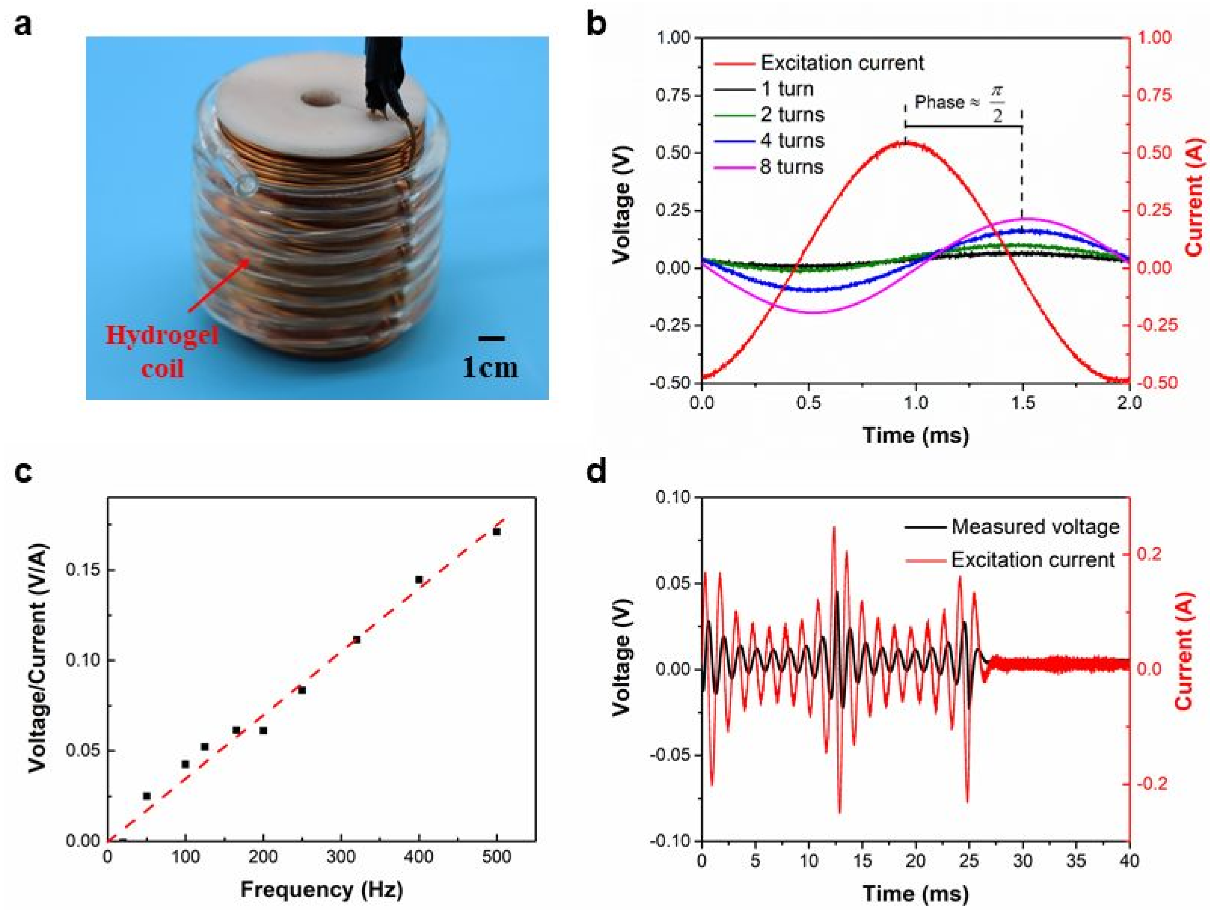

Fig. 3 Ionotronic transformer. a, A metal coil and a co-axial hydrogel coil form an ionotronic transformer. When a sinusoidal electric current is applied to the metal coil, a voltage is induced between the two ends of the hydrogel coil. **b,** The induced voltage between the two ends of the hydrogel coil is linear in the number of its turns, and is behind the applied electric current by a phase of about $\pi/2$. The current, amplitude 0.35 A and frequency 500 Hz, is applied. **c,** The ratio between the induced voltage and the applied current is linear in the frequency of the applied current. A dashed line is drawn to guide the eye. **d,** Besides the sinusoidal excitation, the hydrogel coil responds well to an alternating electric current with multiple components of frequency applied to the metal coil. The hydrogel coil with 8 turns is used in **c** and **d**.

We apply a sinusoidal electric current, amplitude 0.35 A and frequency 500 Hz, to the metal coil. The voltage induced in the hydrogel coil with various numbers of turns is measured as a function of time (Fig. 3b). The induced voltage is linear in the number of turns of the hydrogel coil, and is behind the applied electric current by a phase of about $\pi/2$, which is consistent with Faraday's law, Eq. (1). The ratio between the induced voltage and the applied current of the ionotronic transformer is linear in the frequency of the applied current (Fig. 3c, 8 turns). Furthermore, the hydrogel coil responds well to an alternating electric current with multiple components of frequency applied to the metal coil (Fig. 3d).

In conventional metallic transformers, core of the primary and secondary metal coils is silicon steel of permeability of $\sim 10^{-3}$ H/m, so that the inductance-to-resistance ratio is high, and the energy efficiency is typically more than 95%.[21] By contrast, in the ionotronic transformer, the two coils are separated by air and elastomer of permeability of $\sim 10^{-6}$ H/m, so that the inductance-to-resistance ratio is low, and the energy efficiency of the ionotronic transformer is much lower than that of the conventional metallic transformers (Fig. S3). Detailed estimation of the energy conversion efficiency can be found in the supplementary information.

Noncontact Power Transmission and Motion Detection

The ionotronic transformer is capable of noncontact power transmission. We place a hydrogel coil sealed by a dielectric tube on top of a metal coil and connect the two ends of the hydrogel coil to fifty light-emitting diodes in series (Fig. 4a). When a sinusoidal electric current, amplitude 150 A and frequency 162 kHz, is applied to the metal coil, all the diodes light up (Video 1). We also connect the hydrogel coil to an oscilloscope to measure the generated voltage. When the sinusoidal electric current is applied to the metal coil, the generated voltage is recorded as a function of time (Fig. 4b). One can connect the ionotronic transformer to an ionic device and transduce signals between electrons and ions.

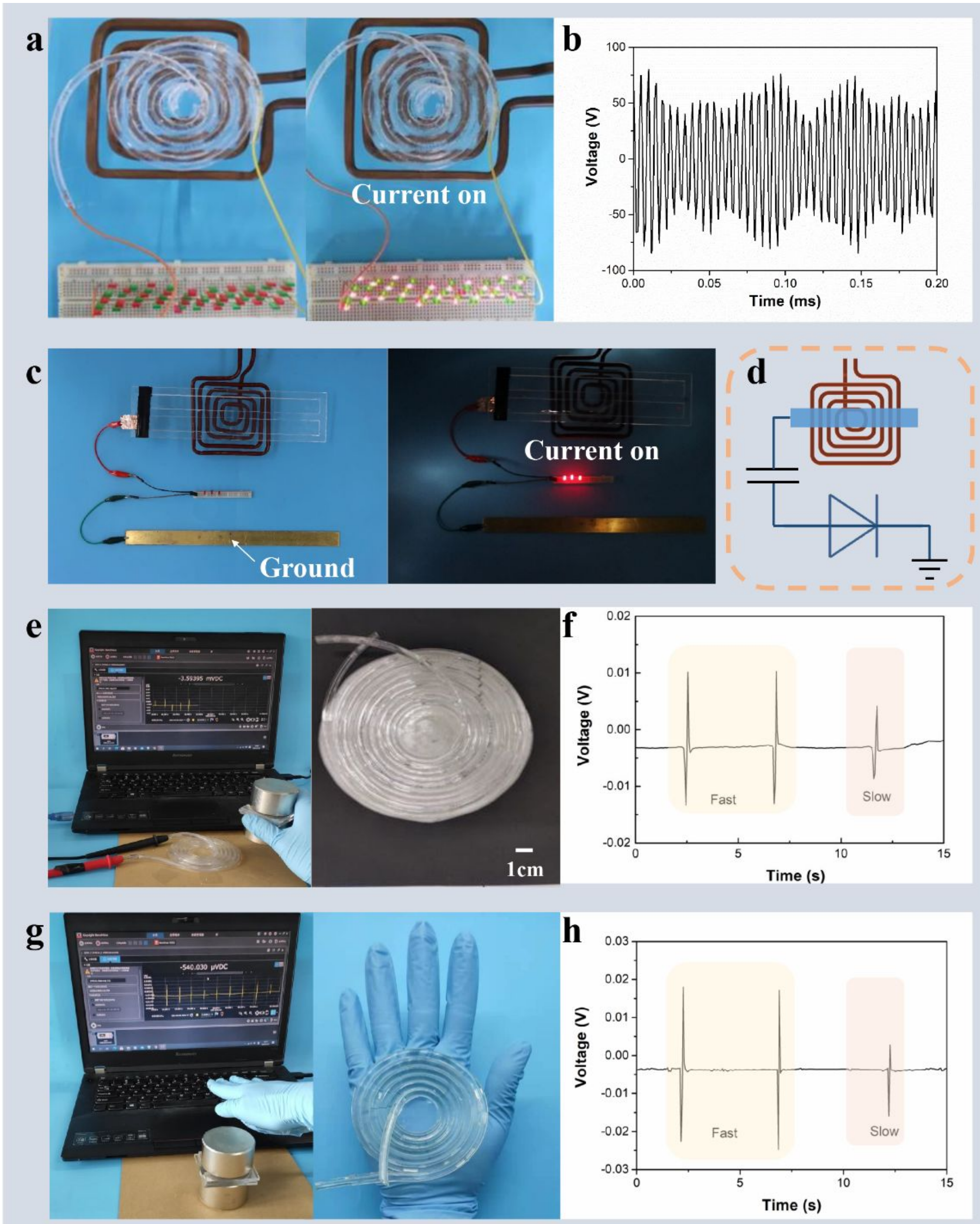

Fig. 4 Noncontact power transmission and motion detection. a, A hydrogel coil sealed by a dielectric tube is placed on a metal coil to form an ionotronic transformer. The hydrogel coil is connected to fifty light-emitting diodes in series. When a sinusoidal electric current is applied to the metal coil, all the diodes light up. **b,** Now the hydrogel coil is connected to an oscilloscope. When a sinusoidal electric current is applied to the metal coil, the oscilloscope displays the generated voltage as a function of time. **c,** A hydrogel line in an acrylic mold is placed on top of a metal coil, and is in contact with a single metallic electrode. The electrode is connected to three light-emitting diodes in parallel, which are connected to the ground. When a sinusoidal electric current is applied to the metal coil, the diodes light up. **d**, Effective circuit of the setup in **c**. **e**, When a permanent magnet moves relative to a hydrogel coil placed on a dielectric surface, a voltage is generated between the two ends of the hydrogel coil. **f**, The generated voltage increases with the velocity of motion. **g**, A hydrogel coil is attached on the surface of a rubber

glove, and a permanent magnet is placed nearby. When the hand wearing the glove moves, a voltage is generated between the two ends of the hydrogel coil. **h**, The generated voltage increases with the velocity of motion.

The magnetoionic transduction can also operate when the hydrogel is in contact with a single metallic electrode. A hydrogel line in an acrylic mold is placed on top of a metal coil and is in contact with a single metallic electrode. We connect the electrode on the hydrogel to three light-emitting diodes in parallel, which are connected to the ground (Fig. 4c). When a sinusoidal electric current, amplitude 150 A and frequency 162 kHz, is applied to the metal coil, the diodes light up (Video 2). Effective circuit of this setup is shown in Fig. 4d.

We next demonstrate that the magnetoionic transduction can be used for noncontact motion detection. A hydrogel coil sealed in a dielectric tube is placed on a dielectric surface. When a permanent magnet moves relative to the hydrogel coil, a voltage is generated between the two ends of the hydrogel coil (Fig. 4e; Video 3). The voltage increases with the velocity of motion and its polarity depends on the direction of motion (Fig. 4f). Furthermore, the hydrogel is soft, and can be attached on the surface of a rubber glove to detect motions of a hand. A permanent magnet is placed nearby. When the hand wearing the glove moves, a voltage is generated between the two ends of the hydrogel coil (Fig. 4g; Video 4). The voltage increases with the velocity of motion (Fig. 4h). One can also place multiple electrodes on the hydrogel and record their voltages relative to the ground. Such an electrode array can record movements in position and time.

The ionotronic transformer is soft and flexible (Fig. S4; Video 5), and transduces signals through ions, making the ionotronic transformer convenient for sensing and communication for curved surfaces, such as engineering structures and biological tissues.

Conclusion

We have developed transduction between magnets and ions. When a hydrogel is in the presence of a time-varying magnetic field, ions in the hydrogel move and an open-circuit voltage is measured between the two ends of the hydrogel. We have studied the physics of the magnetoionic induction using an electromagnetic coil and shown that the generated voltage is independent of the concentration of ions in the hydrogel and is linear in the alternating current applied to the electromagnetic coil. We have designed an ionotronic transformer, in which an alternating electric current applied to a metal coil induces an alternating ionic current in a hydrogel coil. The ionotronic transformer is capable of noncontact power transmission between electrons and ions. We also demonstrate magnetoionic transduction for noncontact motion detection.

Methods

Preparation of Hydrogel. Polyacrylamide hydrogel was made by pouring the hydrogel precursor into a 3 mm thick acrylic mold glued on a plastic substrate. The precursor was an aqueous solution of acrylamide (AAm) as the monomer (2 mol/L), sodium chloride (0.02 mol/L, 0.2 mol/L, or 2 mol/L) as the ionic charge carrier, N,N'-methylenebisacrylamide (MBAA, 0.1% the weight of AAm) as the crosslinker, N,N,N',N'-tetramethylethylenediamine (TEMED, 0.1% the weight of AAm) as the catalyst, and ammonium persulfate (APS, 0.17% the weight of AAm) as the initiator. A glass sheet was used to seal the mold. The precursor was cured at room temperature for 8 hours. It has been well studied that the amount of the crosslinker and catalyst will affect the mechanical properties of the hydrogel, such as Young's modulus and fracture toughness. In a series of papers,[18-20] such mechanical properties of the hydrogel have been studied.

Preparation of Hydrogel Coil. The hydrogel coil was made by injecting the precursor of the polyacrylamide hydrogel into a polyurethane tube with diameter of 5 mm and thickness of 1 mm, and was cured at room temperature for 8 hours. The procedure for the preparation of hydrogel coil was shown in Fig. S1a. We injected the precursor solution of the hydrogel into the dielectric tube slowly from one end of the tube until the precursor solution flowed out from the other end. After the injection, no air bubble was observed in the tube by naked eye (Fig. S1b). In our experiment, the relative humidity in the environment was about 10%. The hydrogel was sealed in an elastomer tube with metal electrodes at the two ends, so that evaporation was slow. We have used the hydrogel coil over one month without appreciable loss of water. Furthermore, several strategies have been reported to retard evaporation. For example, ionic liquids have extremely low vapor pressures and evaporate negligibly.[22] Also, a combination of a hydrogel of high salt content and elastomer seal can prevent the loss of water.[23]

Measurement of the Voltage Generated by an Electromagnetic Coil. A hydrogel was placed on top of a metal coil and was in contact with two metallic electrodes. The resonance frequency of the metal coil was 162 kHz. We supplied an alternating current to the metal coil using an instrument (Easyheat 224, Cheltenham Induction Heating), which automatically detected the resonance frequency of the metal coil and then fixed the frequency of the applied current to this value. Effective value of the current was set and adjusted by the instrument. An oscilloscope (DSOX-3012T, Keysight) was used to measure the voltage between the electrodes at the two ends of the hydrogel.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgements

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