Intelligent material advances energy technologies

Josh Collins and Howard Bell

Highly uniform, rare-earth-based nanocrystals of various sizes and morphologies can be programmed to convert wavelengths throughout the spectrum, providing energy and information where needed.

On the most basic level, our world functions on the conversion of energy and the interpretation of that energy as information. The ability of a species to use these energies efficiently in an always-changing environment is a significant determinant of evolutionary success. As technologies rapidly advance, so does our knowledge, and many prevailing truths and realities are found to be wrong: Helios does not take the Sun across the sky on his chariot, and the world is not flat. One might assume that, similarly, what we perceive as reality in 2014 will seem absurd a thousand years from now.

The Roman poet Ovid metaphorically described the declines in human civilizations in terms of the decreasing value of metals: gold, silver, bronze, and iron. History may describe our current period as an age of hydrocarbons: i.e., petroleum, which underlies our economy and our society. We pump it from the ground and refine it to power cars and airplanes, shape it into plastic bottles and other materials, and fight wars over its sources. These sources are finite, however, and will ultimately have to be replaced with other forms of energy.

Thus, much like sequoia trees that live thousands of years, human survival and evolution will be based on new ways of converting energy and interpreting the knowledge derived. Photons, elementary particles encompassing the electromagnetic spectrum, travel through space in a wave that provides energy. Currently, we perceive only a minuscule portion of the wavelength’s spectrum, but the ability to perceive regions currently out of reach (see Figure 1) will provide us with a deeper understanding of how to live longer, healthier lives. Indeed, we may be just a few generations away from this goal. This potential lies in technologies that can be derived from the ability of rare-earth metals to process energy from the electromagnetic spectrum.

Rare earths are indispensable components across many industries, and they facilitate major technological advances.

Typically comprising scandium, yttrium, and the lanthanide series of elements, rare earths are revealing themselves to be the intelligent material of the future. Rare-earth elements, when crystallized in precise ratios at high temperatures, exhibit unique properties unlike any other material known to humans. There are at least 1000 intelligent material crystals in something people wear or carry. They can be synthesized as alloys to provide enhanced magnetic, optical, catalytic, and high-strength and high-temperature properties. For example, high-strength magnets made from neodymium, iron, and boron have been used in a variety of products, including electric motors, wind turbines, and MRI machines. Rare earths play a vital role in limiting greenhouse gas emissions, and they are being explored for applications in the solar industry. For instance, rare earths can absorb near-IR wavelengths outside the normal absorption band of silicon and convert them to visible light that can then be used by a solar cell. These unusual properties are due to inherent gaps in the orbital structure of their 6s and 4f electrons, which are protected by the outer 4d and 5p orbitals and fill the 4f orbitals prior...
Various morphologies of rare-earth-based nanocrystals can be obtained that exhibit narrow size distributions and excellent batch-to-batch consistency. Scale bar represents 100nm.

to the 5d orbitals. It is this unique electron configuration that separates the lanthanides from the rest of the periodic table, and they are essential in technologies used in medical imaging and diagnostics.2–4

In terms of the particle nature of light, upconversion implies the absorption of two or more low-energy photons to yield the emission of a higher-energy photon. For example, certain rare-earth crystal compositions can be exposed to IR light and emit visible light. Alternatively, downconversion crystals can convert energy over extreme energy levels: they can transform x-ray light into IR light. In addition, the crystallized materials can store energy and emit photons over a controlled period of time in a process called photostimulated luminescence (PSL). PSL occurs through the creation of electron traps in the crystal lattice that undergo electron-hole pair recombination events as a result of carrier and electron interactions. Either photons in the crystal lattice can be absorbed, generating free carriers, or they can initiate recombination and subsequent photoemission at another wavelength. In examples of afterglow materials, the rare-earth dopants are the primary acceptors undergoing a thermal energy transfer to another metal in the host lattice. This radiative transfer can occur within minutes to hours depending on the composition and the crystal-field strength of the emitting ions.

In our work, we synthesize highly uniform, rare-earth-based nanocrystals of various sizes and morphologies (see Figure 2) to yield exceptional electromagnetic up- and downconversion

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properties. Our synthetic methods for controlling particle morphology and composition provide a tool for precise analytical assessment of almost any experimental system using specific wavelengths and intensities of light for identification and quantification. This tunability of the crystal structure provides vast multiplexing capabilities based on the temporal properties of the crystal. The energy-converting crystals can be grown to any shape or size with the photonic property of converting almost any wavelength to any other wavelength (see Figure 3). The lifetime detection of these materials can be controlled through two methods, chemical composition and morphology. For example, two crystals of identical chemical composition but different morphologies will possess a unique lifetime signature inherent to that shape. This adds another customizable layer to the optical complexity of these materials.

Human longevity depends on early detection of diseases, faster computing, and more efficient solar cells, turbines, LEDs, and other green technologies. The extraordinary properties of rare-earth metals make them uniquely suited for research to this end. We can functionalize the surface of synthesized nanocrystals with various ligands, making the crystals stable in many polar and nonpolar solvents for use in a variety of industries. Surface modifications also include the attachment of antibodies or proteins to the nanocrystals, creating a diagnostic beacon to signal the presence of cancers, bacteria, viruses, or DNA. Our current efforts focus on the application of rare-earth metals in the areas of energy generation and intelligent material.

Author Information

Josh Collins and Howard Bell
Intelligent Material Solutions Inc.
Princeton, NJ

Josh Collins is a founding partner and chief technology officer of Intelligent Material Solutions Inc. He is the crystallographer who designs and synthesizes the materials. He is a guest researcher at the National Institutes of Health and has been published in Proceedings of the National Academy of Sciences of the United States of America, Nature, and other peer-reviewed journals.

Howard Bell is a founding partner of Intelligent Material Solutions Inc. who has been working with phosphors for over 25 years. He has designed materials for numerous government agencies and Fortune 500 companies.

References