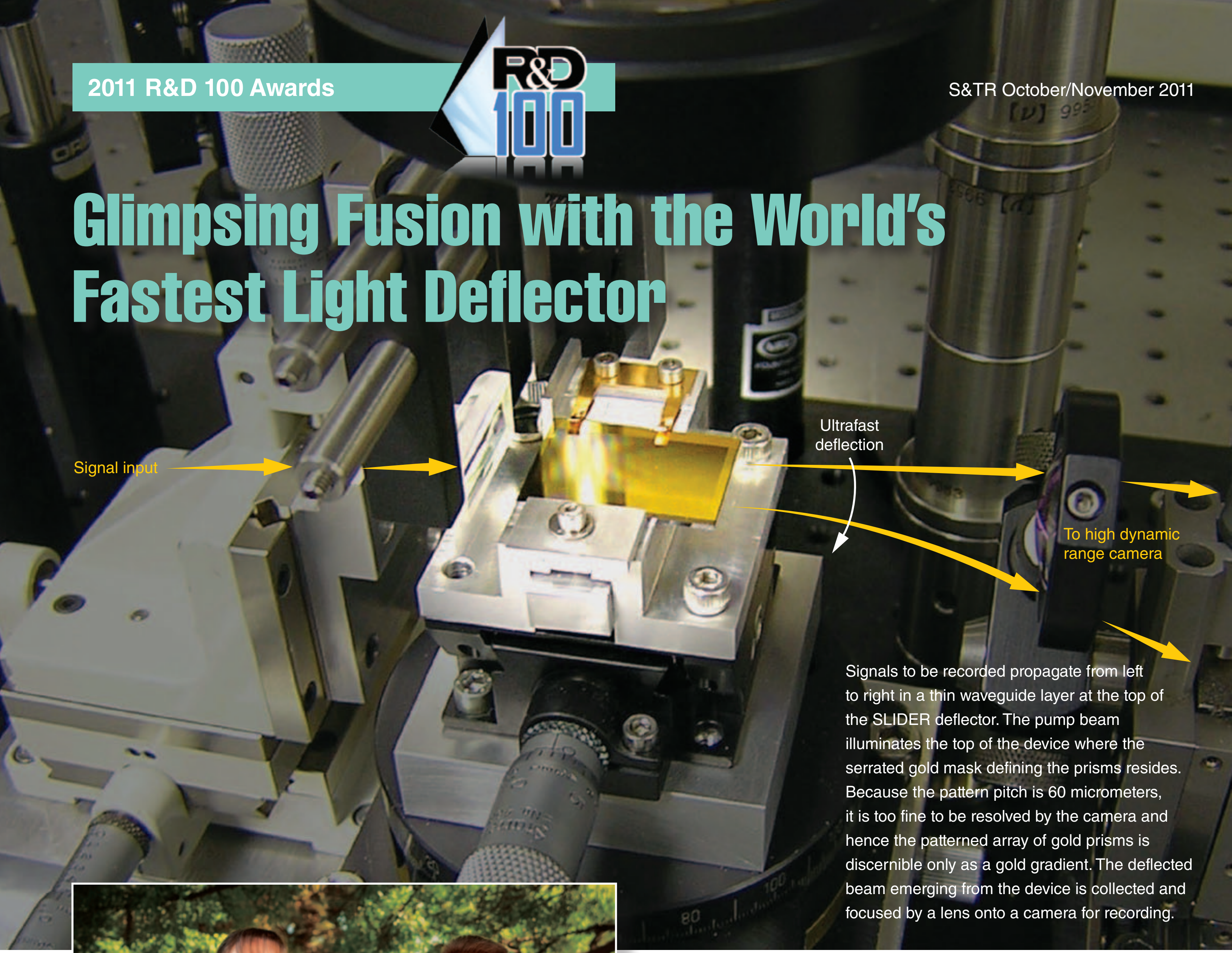
Glimpsing Fusion with the World's Fastest Light Deflector



Signals to be recorded propagate from left to right in a thin waveguide layer at the top of the SLIDER deflector. The pump beam illuminates the top of the device where the serrated gold mask defining the prisms resides. Because the pattern pitch is 60 micrometers, it is too fine to be resolved by the camera and hence the patterned array of gold prisms is discernible only as a gold gradient. The deflected beam emerging from the device is collected and focused by a lens onto a camera for recording.

The Livermore development team for the serrated light illumination for deflection-encoded recording system (SLIDER): (from left) Susan Haynes and John Heebner.

FUSION, the world's great promise for a source of clean and virtually limitless energy, could replicate the very process that powers the stars to meet our most pressing needs on Earth. Lawrence Livermore's National Ignition Facility (NIF) is conducting experiments aimed at achieving fusion ignition and energy gain, the process whereby more energy is released than is required to initiate the fusion reaction. To better understand the physics of fusion and determine the minimum laser input energy needed to start the fusion process, researchers need to acquire accurate details of the burning plasma inside fusion targets. Recording such data with both fine time resolution and high dynamic range, however, presents enormous challenges for existing instruments given the trillionths-of-a-second time frames at which these reactions will occur.

A novel solid-state optical device developed at the Laboratory by engineers John Heebner, Susan Haynes, and Chris Sarantos (formerly of Livermore) may provide a solution to the problem.

The serrated light illumination for deflection-encoded recording (SLIDER), recently honored with an R&D 100 Award, is the world's fastest light deflector. When mated to an ordinary camera, it can record optical signals on picosecond (trillionth of a second) timescales. When combined with a high dynamic range camera, SLIDER can maintain this high temporal resolution and a high dynamic range—two performance parameters that are difficult to meet simultaneously.

This unique combination of high resolution and dynamic range will be crucial for better understanding reactions that occur under the extreme conditions—such as temperatures of more than 100 million degrees Celsius—needed for the tritium–deuterium fuel to "ignite" in a NIF target and undergo thermonuclear burn.

"We're in the infancy of trying to understand the fusion process," says Heebner, likening the effort to that of devising the internal combustion engine more than 100 years ago, both in terms of its potential to revolutionize human society and the challenges faced during its development. Scientific advances at all levels, he explains, rely not only on great ideas but also on access to the right instruments.

"Fusion reactions at NIF will last only several tens of picoseconds," Heebner says. "At such a brief timescale, the availability of commercial instruments to record these signatures with high fidelity is extremely limited or nonexistent. We thus have to develop our own tools." Initial efforts for this work were funded by Livermore's Laboratory Directed Research and Development Program.

Overcoming Limitations of Existing Technologies

Oscilloscopes represent the majority of commercial high-speed recording instruments used to capture extremely short-lived signals. Electron-beam-based streak cameras offer the ability to record even finer details. These instruments use electric fields to sweep electron beams, much like in cathode-ray-tube television sets. They can record data at picosecond timescales but are inherently limited by what are known as space-charge effects—the signal blurring that inevitably occurs when charged particles repel each other. The stronger the signal, the worse the blurring effect and, therefore, the more limited the instruments' useful dynamic range.

Enter SLIDER, whose beam consists not of charged electrons but of uncharged photons. The underlying idea is not new. Scientists have used optical beams to avoid the space-charge effect for decades. But it took what Heebner calls "a flash of insight" to devise an optical version of the streak camera that has the capability of deflecting light rapidly enough to achieve picosecond resolution.

While the signals from fusion reactions are too fast to be recorded by conventional electronic instruments, they are also too slow for spectral techniques now being used in ultrafast laser physics with characteristic timescales of femtoseconds. "SLIDER complements existing technologies and bridges the gap between conventional streak cameras and spectral-based ultrafast recording techniques," Heebner says.

It's All in the Prisms

At the heart of SLIDER lies a solid-state optical deflector that rapidly activates an array of prisms for each sweep repetition. The signal to be recorded rides on a beam of light sent through a 1-centimeter-wide semiconductor planar waveguide that is less than 1 micrometer (1 one-hundredth the width of a human hair) in height. A separate pump laser directed in from above rapidly modifies the waveguide's optical properties. The pump beam is first passed through a serrated mask just above the waveguide. While the signal is traversing the waveguide, the patterned pump beam imprints an array of more than 100 prisms.

At this point, time of flight does the rest. Because the earlier portions of the signal have advanced farther along the waveguide at the moment of prism creation, they are deflected the least. The later portions, however, see more activated prisms and are hence deflected the most. This sweeping beam is then collected and focused by lenses for recording on a conventional camera. The waveguide and serrated pattern are created using ordinary semiconductor growth techniques and contact photolithography, making the SLIDER deflector fabrication relatively inexpensive.

SLIDER can be used to monitor the brilliant x-ray bursts streaming from NIF fusion targets using radiation-to-optical encoders, also developed at the Laboratory, inserted in front of the device. In addition to its application in fusion energy science, SLIDER might be used to characterize high-bandwidth, long-haul telecommunication systems, chemical reactions, particle accelerators, and short-pulse lasers.

The development of fusion energy is one of the most difficult science and engineering challenges ever undertaken. Scientific insights, however, often depend on access to better diagnostic instruments. The insights this new technology will provide may help the Laboratory achieve this grand challenge and advance scientific knowledge across many disciplines.

—Monica Friedlander

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