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Thin Film Helps Detect Gravitational Waves

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Specialized mirror coatings help confirm Einstein's century-old prediction.

It's only a slight exaggeration to say that a few layers of molecules helped make possible one of the most important physics observations of the past several decades.

Those layers of metal oxides—which barely add up to 2 μm in thickness—coat the highly specialized mirrors that make up the Laser Interferometer Gravitational-Wave Observatory, or LIGO. The coatings make LIGO's mirrors exceptionally reflective, enabling the enormous pair of optical instruments to detect gravitational waves.

Gravitational waves are curious entities described as "ripples in spacetime" that radiate for billions of light-years as they traverse the universe. Albert Einstein predicted their existence in 1916 in his general theory of relativity. But it took a century until scientists were able to confirm that prediction experimentally. Last year, researchers reported that the ultrasensitive LIGO detectors, one of which is located in Livingston, LA, the other in Hanford, WA, finally detected these elusive waves.

In his theory, Einstein described gravity in terms of warped spacetime. Some physicists like to depict that warping like the way a trampoline sags under the weight of a heavy bowling ball. If someone rolled a second, lighter ball across the warped trampoline, that ball would orbit and spiral in toward the heavier one, in a manner similar to the effects of gravity on celestial bodies. The 100-year-old theory predicts that, as gargantuan bodies such as supernovae and black holes accelerate because of gravity, they will emit vast amounts of energy and generate gravitational waves that propagate through the universe, sometimes passing through Earth.

Detecting those waves turned out to be an extraordinary experimental challenge. Scientists at LIGO started looking for gravitational waves in the early 2000s. For years, they monitored their instruments, searching for telltale but minuscule signs of the waves. But they saw none.

The 4-km-long arms of the LIGO interferometer seen here extend into the green countryside of Livingston, LA. Hanford, WA, hosts a second, nearly identical instrument. Credit: LIGO.

So over the course of several years starting in 2008, the team of more than 1,000 scientists from California Institute of Technology, Massachusetts Institute of Technology, and many other research centers overhauled LIGO's equipment. These improvements included replacing the mirrors with new advanced ones coated in that thin layer of metal oxides.

To understand why that 2-μm-thick coating played such an important role in spotting gravitational waves, consider the measurement that LIGO's instruments were tasked with. Like Fourier transform infrared (FTIR) spectrometers, LIGO's detectors send light through a beam splitter that directs the two beams along a pair of arms oriented 90° apart. But unlike benchtop FTIRs, which use centimeter-sized interferometers, the arms in LIGO's instruments measure a whopping 4 km. And the LIGO detectors don't probe molecules. They're designed instead to measure with extreme accuracy momentary subatomic-scale changes in the length of one arm relative to the other.

What causes such minuscule changes in the arm's lengths? According to Einstein's theory, as gravitational waves pass through Earth, the spacetime ripples will subtly change the length of objects such as LIGO's arms.

Here's how LIGO detects those events. A 120-mm-wide beam of laser light bounces back and forth between a pair of mirrors suspended at both ends of the 4-km arms. A portion

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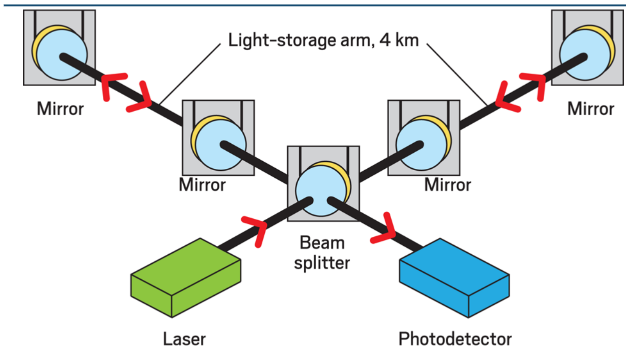
of the bouncing beams combines and travels to a photodetector. In the absence of gravitational waves, the beams interfere destructively, yielding no signal. A tiny change in the relative lengths of the arms results in constructive interference, leading, in principle, to signals that can be detected.



As laser light bounces back and forth along arms between its mirrors, LIGO senses gravitational waves as minuscule fluctuations in the lengths of the arms. Credit: C&EN.

But actually measuring those signals requires heroic effort in eliminating multiple tiny sources of noise, says LIGO chief detector scientist Peter K. Fritschel. For example, the bouncing laser beam can heat and deform the mirrors ever so slightly and can cause them to move a tiny distance. Heavier mirrors are less prone to generating those types of noise than lighter ones. So during the overhaul, the LIGO team replaced the original 11-kg mirrors with wider, thicker 40-kg fused silica ones. And they upgraded the equipment that prevented environmental vibrations and seismic activity from jostling the mirrors.

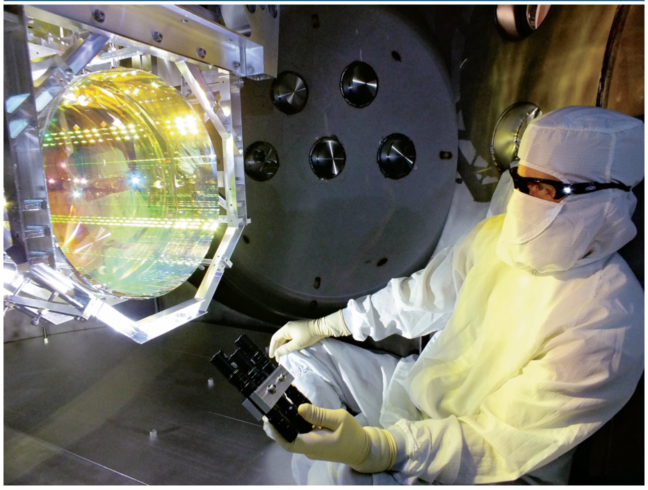
They also sought the best coatings possible to ensure that the mirrors remain exceptionally reflective to keep the light trapped in the interferometer arms. Doing so maintains the beams' intensity, thereby maximizing the chance of detecting tiny gravitational wave signals. "The coatings present their own set of challenges and have multiple constraints that need to be addressed", Fritschel stresses. For example, the material must minimize losses resulting from absorption and the scattering caused by room temperature molecular vibrations in the coating—thermal noise. And the material must be compatible with technologies that apply thin coatings.

Working with LMA, a specialty coatings research center based at Claud Bernard University Lyon 1, in France, the team decided to apply a total of 30 alternating layers of SiO_2 and TiO_2-doped Ta_2O_5. Those two materials pair well for this application, Fritschel explains, because in addition to their low absorption, they exhibit a large difference in index of refraction, which enhances the coating's reflectivity. Doping with TiO_2 further boosts the difference in index of refraction. LMA deposited the films via ion-beam sputtering, which produced ultrasmooth coatings on the mirror surfaces. Various tests show that LIGO's overhaul improved its sensitivity for detecting gravitational wave signals by roughly a factor of 3, according to Gregory M. Harry, an American University physicist and former chair of the LIGO optics working group.

So, in September 2015, just days after the upgraded instruments—referred to as Advanced LIGO—came online, the team saw exactly what it had been waiting for. At first, no one believed it was real.

When Harry first saw the signal, he thought it was just another dry run—fake results injected in the data stream to test the equipment and the team's ability to recognize such signals.

Caltech's GariLynn Billingsley thought the same thing, "or maybe that it was a hoax", she says. Billingsley is a senior optical engineer who managed the design, fabrication, and test of some of LIGO's optical components.



Enormous mirrors such as the one being examined here have enabled the LIGO detectors to spot gravitational waves. Credit: LIGO.

The team quickly ruled out those possibilities, and as Harry says excitedly, "there was very little room for doubt we actually detected gravitational waves. I could not believe this was really happening."

The researchers then scrutinized the signals, which were detected nearly simultaneously by the twin instruments on opposite sides of the U.S. They concluded that they had detected gravitational waves that were generated 1.3 billion years ago as two black holes—roughly 29 and 36 times the mass of the sun—merged, forming a single black hole.

That detection feat marked the first time gravitational waves were observed directly and the first observation of a pair of black holes merging.

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LIGO statisticians cautioned the team that it might take months to detect another event. But the next one occurred just 2 weeks later. Those signals were less convincing, Harry says, so the team did not publish the results.

But near the end of December 2015, LIGO researchers conclusively detected a second black-hole merger. Dubbed the Boxing Day event, the energy burst, which the team reported last summer, was caused by the coalescence of black holes 8 and 14 times the mass of our sun 1.4 billion years ago.

With those first big successes behind them, the LIGO team is eager to learn more about gravitational waves and black holes, as well as possibly detect neutron-star mergers and other astrophysical events that generate the spacetime ripples. And to do that, they want to further improve their equipment, including the mirror coatings. That may come from advances in molecular-level understanding of the coatings, which remains an area with several unanswered questions.

For example, doping with TiO_2 reduced thermal noise in the coating, but the mechanism is unclear. Understanding that mechanism could guide further coating improvements. According to Harry, doping seems to make the average bond distances between tantalum, titanium, and oxygen somewhat more regular, even though the material remains noncrystalline.

"We have clear data showing the material becomes less amorphous upon doping", he says, but how this structural change is related to reducing thermal noise remains an open research question. Also not well understood is the effect of annealing, which further improves the film's properties.

LIGO scientists are ecstatic that, after decades of searching for gravitational waves, they detected them conclusively with their refurbished detectors, thereby launching a new era of astronomy. But they are hoping to further improve their detection sensitivity—and ideal optical coatings seem to be the key.

As Billingsley puts it, "We are appealing to chemists, materials scientists, and others to help us make better coatings and figure out what's going on in these films at the molecular level."

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