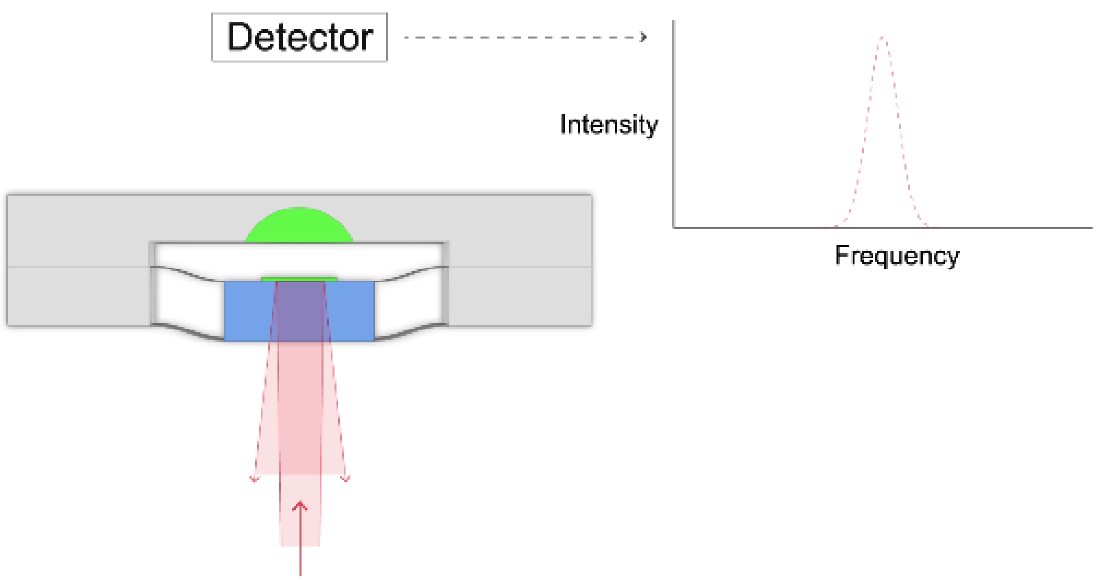
Measuring acceleration with light

March 31 2017, by Ben Stein



Most people have never seen an accelerometer—a device that measures change in velocity—and wouldn't know where to look. Yet accelerometers have become essential to modern life, from controlling automobile airbags, to earthquake monitoring, inertial navigation for spaceflight, aircraft, and autonomous vehicles, and keeping the screen image rotated the right way on cell phones and tablets, among other uses. Not surprisingly, demand is rising for inexpensive, high-precision instruments that can be embedded in ever-smaller locations.

That is why NIST researchers have developed and are testing a novel silicon-based optomechanical accelerometer less than 1 millimeter thick. It is designed to deliver measurements directly traceable to the SI with uncertainties better than 1 part in 1000—"as good as any laboratory acceleration device in the world," says project scientist Thomas LeBrun of NIST's Physical Measurement Laboratory.

Accelerometers typically function by measuring the change in position of a free-mounted "proof mass," typically a solid block, relative to some fixed point of reference inside the device. If the system is at rest or moving at constant velocity, the distance between the proof mass and the fixed reference point will not change. Analogously, the distance between the dashboard and a front-seat passenger in a car doesn't change while driving at a steady 60 kph.

But if the accelerometer speeds up or slows down, the separation between the proof mass and the reference point either increases or decreases. Similarly, when the car's driver suddenly hits the brakes, the passenger is shifted forward toward the dashboard, putting pressure on the seat belt.

Accelerometers convert that kind of displacement to a measurable signal of some sort. For example, movement of the proof mass might compress a piezoelectric material, generating a current, or it might stretch a sheet of insulator so that its electrical resistance increases. The devices have now shrunk to the size at which they can be fabricated using technology in widespread use to make microelectromechanical devices (MEMS) and microelectronics.

The new NIST device uses infrared (IR) laser light to measure the change in distance between two facing, highly reflective surfaces separated by a very small empty space in the center. (See animation.) On one side is the proof mass, a square slab of silicon with a flat mirror coating on its inner face, suspended within the cavity by tiny flexible beams on the top and bottom edges which act as springs, allowing the mass to move relative to its surroundings when the device experiences an acceleration.

On the other side of the empty space is a fixed hemispherical concave mirror, facing inward toward the proof mass. This kind of facing-mirror arrangement constitutes what is called a Fabry-Perot cavity.

When IR light is initially sent into the cavity, nearly all of it is reflected—except for one particular wavelength that is exactly the right size to reflect back and forth between the two mirrored surfaces and resonate, forming a standing wave and increasing in intensity by a factor of a thousand so that enough light is transmitted by the cavity to be detected. The wavelength of the resonant wave is determined by the distance between the two mirrors, much as the pitch of a trombone note depends on how far the slide is extended or retracted.

"The optical method provides much better sensitivity and lower uncertainties," says LeBrun, "because, among other reasons, we can control and measure the wavelength of light to very high accuracy."

MEMS-based Fabry-Perot configurations have been tried before for small accelerometers, typically with the mirrors mounted in two parallel planes facing each other. "That's challenging," LeBrun says, "because it's very difficult to make that kind of design extremely precise. If one of the mirrors does not focus the light into the cavity, the light is lost much more rapidly, reducing the precision. In our design, high quality mirrors keep the light in the cavity, while the proof mass—suspended by flexible beams about one-fifth the width of a human hair—is designed to act as an ideal spring. That maximizes stability, and eliminates potential rocking motion, allowing for higher-sensitivity measurements."

Except for mirror coatings and the silicon nitride beams holding the proof mass, all of the accelerometer components are made of silicon, which has several advantages. One is the ready availability of proven technologies for shaping and processing silicon to high tolerances in small dimensions.

That is important for the NIST design, in which the fixed hemispherical mirror is about 300 micrometers (µm) deep, 500 µm wide, and has a surface smoothness that varies by no more than 1 nanometer. (The accelerometers LeBrun and colleagues used for experiments were fabricated at NIST's Center for Nanoscale Science and Technology.) In addition, silicon provides very good thermal stability and is transparent to IR light.

The laser light source is placed behind the proof mass on one side of the device; on the other side, behind the hemispherical mirror, is a light sensor/detector. The laser is "tunable," capable of producing a range of IR wavelengths. During acceleration, as the distance between the proof mass and the hemispherical mirror changes, the laser wavelength tracks the resonant wavelength of the cavity. As a result, the laser gives a direct, fast, and highly accurate readout of the proof mass motion.

The measurements must be extremely precise. "Changing the cavity length by less than 1 nm completely extinguishes the optical resonance," says project scientist Jason Gorman.

Because the sensor operates using a laser with a well-characterized wavelength, it can be intrinsically self-calibrating. And because the components and manufacturing methods are the same size as those routinely used in microelectronics or MEMS fabrication, the eventual production cost of a complete unit should be low. But before then, the NIST scientists will have to overcome a number of obstacles.

"One is the demanding time scale involved," Gorman says. "As the cavity dimension changes, the tunable laser will have no more than about 100 microseconds to scan the wavelength over a wide range so that it tracks the cavity motion. Finding an inexpensive laser with those capabilities is another challenge. So is making a robust optical fiber connection to a device that is vibrating at 1000 cycles per second—and eventually perhaps 10 times faster."

"We fully expect this optical microcavity technology to result in field-deployable accelerometers with intrinsic accuracy probably ten times better than currently possible," says John Kramar, the Leader of the Nanoscale Metrology Group. "But what is even more exciting is the wide range of other types of sensors and applications that this technology could dramatically improve, including ultrasound, microphones, altimeters, pressure sensors, gyroscopes, and geophysical exploration."

More information: An Optomechanical Accelerometer with a High-Finesse Hemispherical Optical Cavity. dx.doi.org/10.1109/ISISS.2016.7435556

Provided by National Institute of Standards and Technology