Ultra-sensitive thermometer based on a compact optical resonator

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This article demonstrates a thermometer based on millimeter-scale crystalline disk optical-resonator. By measuring the relative speed difference between 2 colors of light that travel inside the disk, the temperature changes of the disk was measured with a precision of 30 billionths of a degree.

In our recent study1 we used a whispering-gallery-mode resonator (WGMR) to demonstrate a thermometer based on optical resonator with superb sensing resolution. Optical resonators have long held an important position in laser frequency stabilization applications such as optical clocks and spectroscopy metrology. In the past 2 decades, a novel type of resonator, the WGMR has attracted extensive interest in various fundamental and applied researches including laser frequency stabilization.2 A whispering-gallery was first named by Lord Rayleigh in 19123 to describe the acoustical phenomenon that was noted when a whispered sound could circulate around the gallery of the dome of St. Paul’s cathedral in London.

In an optical “whispering gallery” the light wave travels inside but very close to the surface of a dielectric disk or sphere and is trapped through total internal reflection. One finds that there is a strong resonance in such a structure when the light color is chosen so that the light wave can constructively interfere with itself after a full round trip. These resonant frequencies provide a set of markers in the optical spectrum and can be used as a frequency reference to stabilize the frequency of a laser. When compared to conventional optical resonators (Fabry-Perot cavities), WGMRs have the advantages of compact size, rigidity and ease of fabrication. Moreover, the surface polishing technique and the low absorption of crystalline materials such as CaF₂ and MgF₂ yield extraordinarily long traveling distances of light wave in the resonator, therefore leading to very narrow well-defined resonant features: this is ideal for frequency stabilization applications. However, temperature fluctuations, of both technical and fundamental origins, limit the performance of such devices because they alter the size of the resonator through thermal expansion together with changing the speed of light in the material through the thermo-optic effect (i.e. the speed of light propagating in crystalline material depends on the temperature of the material).4

In our work, this sensitivity of the resonant frequency to temperature, which is a disadvantage in frequency stabilization applications, has been turned to our benefit by applying the device to the problem of high temperature sensitivity. 2 light beams of different colors (or wavelengths), one of which is infrared (~1064 nm) from a laser, with a second beam generated by second-harmonic process in the green part of the spectrum (~532 nm), were injected into a WGMR through a prism as shown in Figure 1. The 2 frequencies were actively locked to 2 resonant modes in the structure. As the temperature changes, the resonant wavelengths of the WGMR will shift due to both thermal expansion as well as the thermo-optic effect. While thermal expansion is identical for both colors (the change in size of the resonator is the same whether viewed in red or green light), it is critical to understand that the thermo-optic effect varies as a function of wavelength. In other words, the velocity difference between the 2 colors of light depends on the temperature of the resonator. As a result, we can measure temperature by measuring this relative speed difference between the 2 colors.

Superficially, it would have been possible to do this experiment by just measuring the frequency of light of a single mode using modern optical techniques such as the optical frequency comb.5 However, the cost and size of such Nobel-prize winning technology is prohibitive in most temperature measurement applications. Instead, the approach in our study is fully self-referential requiring minimal auxiliary equipment. As experiment results showed, the minimum detectable temperature fluctuation, or the resolution of the thermometer, is 30 Nano-Kelvin in just 1 second, which sets the record for temperature sensing at room temperature to the best of the authors’ knowledge.

One should note that like most precision measurements, this thermometry does not aim to measure absolute temperature but only the temperature changes. One direct application of such thermometry...
would be to keep the WGMR within a limited range of temperature variation, thus stabilizing the resonance frequency. In the follow up experiment, by modulating the input laser power, the measured temperature was kept within a very narrow range, with the temperature fluctuations being highly suppressed. In fact, this suppression was so good that it suppressed the residual fluctuations below the fundamental noise arising out of the Brownian fluctuations that originate from the unceasing motion of atoms in a definite volume.

With certain adoptions, such a thermometer could be developed into a bolometer\(^6\) or a calorimeter.\(^7\) As the world is going more and more “micro” or even “nano” in a wide range of researches and industrial applications, to measure extremely small amount of temperature change or energy change is of crucial importance in areas such as medical research or material engineering. For example, chemical or biological interactions of very small scale can release or absorb a tiny amount of energy, and consequently increase or decrease the temperature by a trace amount. The ability to detect such temperature or energy change will be potentially useful in determining or sensing the interaction, which is vitally attractive. Furthermore, the dual-mode self-reference principle can also be used in other sensing areas such as sensing changes in pressure, humidity, and concentrations of substances of interest, to name just a few.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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