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Photonic Thermometry at PTB – Challenges and Perspectives for Contact Temperature Metrology Utilizing Optical Sensors

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Summary:
Photonic sensors offer new possibilities for the metrological temperature determination in specific applications including high electric fields or harsh environments. Within two EU projects the PTB develop and validate different kinds of photonic thermometers in a temperature range from 0 °C to over 1500 °C. The aim of this work is to develop and validate novel accurate photonic thermometers with uncertainties below 10 mK, and sensors for application within harsh environments at high temperatures. We show first results using silicon ring resonators and sapphire fiber Bragg gratings.

Keywords: photonic thermometry, temperature sensor, sapphire, fiber Bragg grating, whispering gallery resonator

Introduction

In the industrially most relevant temperature range from about −100 °C to 1000 °C temperature measurements are commonly based on the measurement of electrical resistance (e.g. Pt100) or voltage (thermocouple). Photonic sensors, in contrast, use the light-matter interaction to measure temperature. Usually the change of the refractive index and the resulting shift of the resonance wavelength of the corresponding optical resonator is utilized. Fiber sensors using fiber Bragg gratings (FBG) or systems using distributed methods based on scattering processes in optical fibers are industrially available. Nevertheless, the determination and reduction of temperature uncertainty is still a challenging task.

The Physikalisch Technische Bundesanstalt (PTB) is working on special photonic sensors for temperature measurement within two European research projects.

The first project "Enhancing process efficiency through improved temperature measurement 2" (EMPRESS 2) has the overall aim of improving the efficiency of key industrial manufacturing processes through improved temperature measurement and control. The project focuses on accurate and SI traceable temperature measurement with different stable, reliable, durable and robust sensors. One objective is the introduction of traceable fiber optic measurements at high temperatures above 500 °C. PTB is working together with the Leibniz-Institut für Photonische Technolgien (IPHT) on FBGs in sapphire fibers which can be used at temperatures exceeding 1500 °C.

The second project "Photonic and Optomechanical Sensors for Nanoscaled and Quantum Thermometry" (PhotOQuant) deals with fundamental research for high-precision or primary temperature sensors. Two micrometre-sized chip-based techniques are designed, manufactured, characterized and calibrated: optomechanical sensors, in which the temperature-dependent Brownian motion of nanostructures is optically detected, and photonic resonators, in which planar waveguides (e.g. ring resonators) allow very high-resolution measurements of the refractive index change. Together with the Leibniz-Institut für innovative Mikroelektronik (IHP), PTB investigates Si / SiO_2 structures which are manufactured by standardized masking processes.

Perspective and First Results

The well-established methodologies of the International Temperature Scale of 1990 (ITS-90) defines standard platinum resistance thermometers (SPRT) as the interpolating sensors between the defining fixed points (see Fig. 1, top). These thermometers are used in a large temperature range with superior reproducibility and uncertainties below 10 mK (see Fig. 1). Nevertheless, these sensors are mechanical fragile and principally unsuitable for harsh environments with strong electric fields.

Above approximately 1000 °C the ITS-90 is defined by radiation thermometers. These measure the spectral radiance of hot objects according to Planck's law. With ideal radiators (black bodies), uncertainties of less than 1 K can be achieved (see Fig. 1). For measurements on real objects, the emissivity of the surface is required, which here can only be determined with accuracies in the percentage range [5], thus increasing the overall uncertainty of the temperature measurement to about 10 K.

Approaches using photonic thermometers show great potential to reach comparable measurement uncertainties [1] with the additional advantage of a metal free, chemical inert and mechanical robust sensor design. Our efforts are concentrated in two directions, on the one hand the validation and improvement of photonic resonators (PhotoQuant) for moderate environments and temperatures up to 100 °C with measurement uncertainties below 10 mK (see Fig. 1). On the other hand, the metrological characterization of sapphire based fiber Bragg gratings (SFBG) for applications in harsh environments with temperatures above 1500 °C (EMPRESS 2).

Both photonic thermometer principles are mainly based on a determination of frequency (or wavelength) changes of an optical resonance. Using tunable laser for fiber Bragg grating (FBG) interrogation it has been shown, that peak wavelength tracking with an uncertainty below 1 pm is possible with stability better than 4 pm/year [2] and even lower for pre-annealed FBG [3]. Taking the temperature coefficient (≈ 12 pm/K) into account this yields to a temperature uncertainty below 100 mK in temperature range up to 600°C.

Photonic ring resonators offer an even higher temperature coefficient (≈ 75 pm/K) and with improved quality factor of the resonant frequency. According to our results there are suitable for temperature uncertainty quite below 10 mK (see Fig. 1). The most challenging task and critical part to enable low uncertainties is the packaging of the planar photonic devices, due to the stabilization of fiber to chip coupling. Most approaches using for example glue are limited to temperatures up to around 250°C. We actually are working on new package design to exceed this limitation up to approx. 600°C.

Another solution suitable for even higher temperature above 1500 °C (probably up to 1900 °C) are SFBG's, which offer a temperature coefficient of 26 pm/K [4]. Since they are intrinsically multimodal the corresponding resonance spectra is more complex compared to conventional singlemode FBG. Due to that, the precise determination of wavelength shift is the limiting factor for temperature uncertainties (1 K region, see Fig. 1). We therefore developing new methods for probing and signal processing to further reduce uncertainties.

In summary, photonic thermometry sensors are suitable to compete with conventional electrical sensors, however some effort and research have to be done in the future.

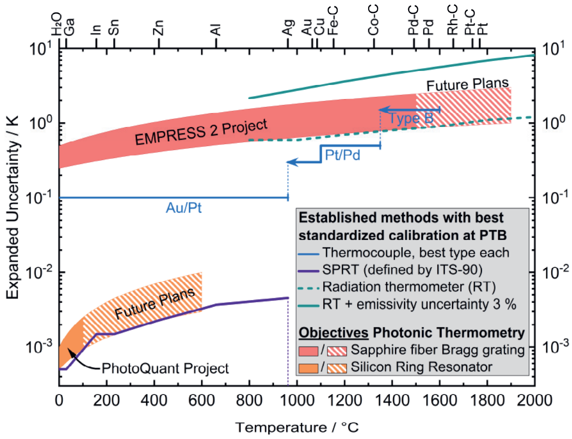

Fig. 1. Accuracy of different temperature measurement techniques: established electrical and radiance methods with the best possible standardized calibration at PTB in comparison to the target uncertainty ranges of the new photonic methods. (See text for details.)

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References

[1] Z. Ahmed, et al., Proc. SPIE 10923, Silicon Photonics XIV, 109230L (12 April 2019), doi:10.1117/12.2505898

[2] S. D. Dyer, et al., Proc. SPIE 5855, 17th International Conference on Optical Fibre Sensors, 88-93 (2005), doi:10.1117/12.623444

[3] P. Mauron, et al., Scientific production and competences - EPFL Theses, EMPA (2001), doi:10.5075/epfl-thesis-2339

[4] D. Grobnic, et al., Proc. SPIE 5855, 17th International Conference on Optical Fibre Sensors, (23 May 2005), doi:10.1117/12.623592

[5] D. Urban, et al., Int J Thermophys 39, 10 (2018), doi: /10.1007/s10765-017-2339-y