Optical Temperature Sensor Based on Whispering Gallery Modes

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We realised a novel optical temperature sensor with polymer microspheres as sensing element. Whispering gallery modes are excited by total internal reflection. Dependent on the temperature the changes of refractive index and diameter cause a shift in resonance position. Thus, a temperature dependent intensity is derived, from which the temperature can be concluded.

The advantages of optical measurement techniques are obvious in every day life. Today a vast number of electronic components in industry, transportation and households emits electromagnetic radiation. This electromagnetic noise can cause malfunctions in electronic sensing components. Optical sensors are insensitive to electromagnetic noise.

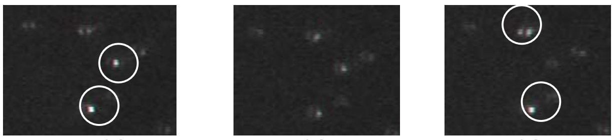
The measuring principle used is the sensitivity of the resonance frequencies in optical microresonators to changes of the optical and geometrical properties of the resonator. The sensor that we have developed measures temperatures. However, the principle can also be used to measure pressure, distances or trace gases etc.

As sensing element we use an array of acryl microspheres with diameters of about 100 to 150 μm. By placing these spheres into an evanescent optical field part of this field tunnels into the spheres and excites resonances if the phase condition is met. The occurrence of optical resonances usually called WGM's (whispering gallery modes) depends on the size parameter and the refractive index of the particles. The size parameter is the ratio of the circumference of the sphere to the wavelength. In the picture of geometrical optics a resonance is excited if a light beam circulating in the sphere by multiple total internal reflection on the surface crosses its path in phase after one roundtrip. The phase is a function of the geometrical path length depending on the size of the particle, the resonance order, the index of refraction of the sphere, and the phase shift by the reflection on the surface. The later is a function of the relative index of refraction. Each resonator can be excited with a number of different frequencies depending on the resonance mode number and the resonance order. Resonances of increasing order have increasing resonance width.

In principle, all physical and chemical quantities that affect one of these parameters can be measured with high sensitivity. In case of resonance the electromagnetic field within the sphere can rise by many orders of magnitude. This increase can be detected either by an increase of the light scattered by the sphere or by a corresponding increase of the light decoupled from the sphere into a waveguide for example. In the paper presented here, the resonator properties are changed by temperature and the scattered light is recorded.

In contrast to previous work where the resonance is detected by tuning the excitation wavelength to the resonance wavelength, we use an array of resonators with slightly different properties that are illuminated by monochromatic light at a fixed wave length.

Changing the temperature causes a change of the refractive index and diameter of the sphere. As a result, while one sphere of the array is tuned to resonance due to the temperature change an other sphere or other spheres of the array are detuned from the resonance. This can be detected by recording the light scattered from the resonator array. An example is shown in Fig. 1. For different temperatures we get different scattering intensities. If an array of particles is used we get a temperature dependent intensity pattern as shown in Fig. 1 from which the temperature can be determined.



30°C 35°C 40°C

Fig. 1: Temperature dependent intensity pattern of different particles

The temperature dependent intensity of each particle is recorded by a CMOS-sensor. Thus, we do not need any frequency selective element such as a spectrograph for signal processing nor a tuneable laser. The intensity scattered by an array consisting of five different resonators is shown as function of temperature in Fig. 2.

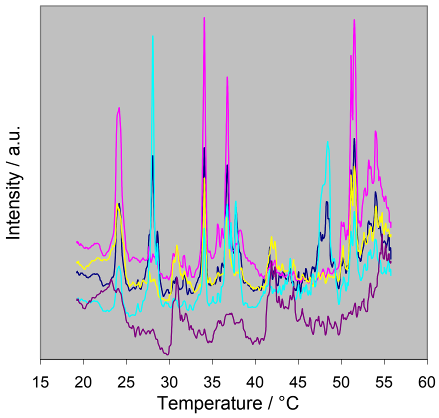


Fig. 2: Temperature dependent intensities of five particles

These particles have slightly different diameters of about 140 µm. Therefore, for a constant wavelength different resonances are excited at different temperatures. By applying four different thresholds to the intensity signals we get digitized codes consisting of 0, 1, 2, 3 and 4, as shown in Fig. 3.

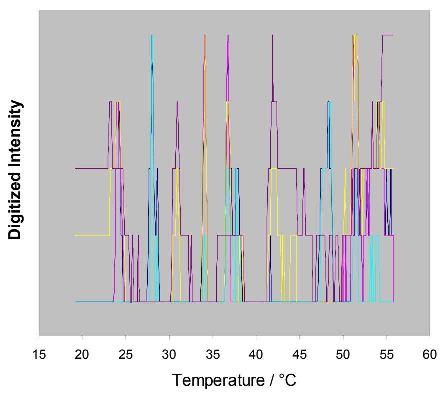


Fig. 3: Digitized temperature dependent intensities of five particles

It is obvious that the more particles the array contains the better the temperature resolution is. Moreover, ambiguous temperature codes can be eliminated. In an experiment with five particles and four thresholds the best result we achieved was an average error of 0,1°C. The maximum error was about 0,4°C.

In order to compare the experimental results with theoretical calculations we developed a temperature dependent resonance condition, from which the shift of resonant wavelength was derived. The model is based on the work of Roll et al. (1). Recently, the temperature dependence of absorbing resonators was investigated by Carmon et al. (2). The calculated shift of resonant wavelength is shown in Fig. 4. The shift has a turning point, where the wavelength turns from shorter to longer wavelengths. This effect is due to the opposite influences of refractive index change and diameter change. At the calculated turning point, here at about 36°C, the changes of refractive index and diameter compensate each other. The shift in the surrounding range becomes very weak and therefore the temperature dependence of the intensity is also weak. In the experiment a lack of resonance shift can be noticed at about 40°C. The slightly different position of the calculated and measured turning point may be caused by the actual experimental dependence of the refractive index change and heat expansion coefficient, which may be slightly different from the corresponding coefficients determined from bulk material and used in the calculations.

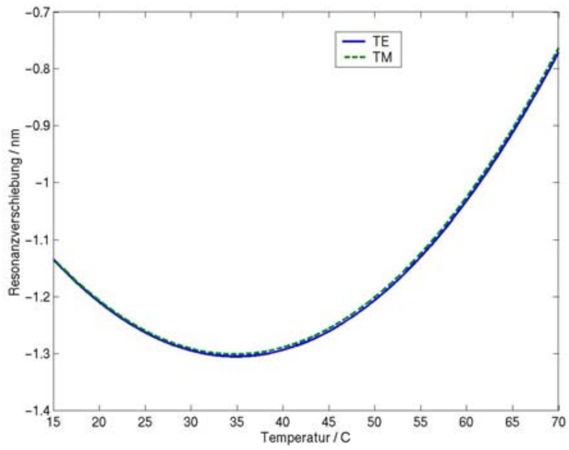


Fig. 4: Calculated shift of resonant wavelength with temperature

The temperature dependence of the sensor is material dependent. Appropriate materials can be chosen that have no turning point in the specific measuring ranges. In contrast, the fact that the resonant wavelength of the resonator used in these experiments shows nearly no temperature dependence around 36°C can be very advantageous if the sensor is used as pressure sensor or as chemical sensor.

In summary, we have developed an optical temperature sensor based on whispering gallery modes in spherical microresonators. This sensor does not require a tuneable laser to excite the resonances nor frequency selective components such as a monochromator to determine the resonance position. In addition, the sensitivity of the sensor can be adjusted by selecting an appropriate number of sensor elements. Experiments with five sensor elements and four digitizing thresholds led to an averaged accuracy of +/-0,1°C. The maximum error was about 0,4°C.

Literatur

[1] G. Roll, T. Kaiser, G. Schweiger: „Eigenmodes of spherical dielectric cavities: coupling of internal and external rays“ in J. Opt. Soc. Am. A/ Vol. 16, No. 4 (1999)

[2] T. Carmon, L. Yang, K. J. Vahala: „Dynamical thermal behavior and thermal self-stability of microcavities“ in Optics Express, Vol. 12, No. 20, 4742-4750 (2004)