Applications of Microwave Resonators to Thermal Metrology

Summary

This thesis deals with two applications of microwave sensing devices to thermal metrology. In the first case, a Whispering Gallery Mode (WGM) resonator is used as a sensor for temperature measurements. In particular, the prototype sensor is made of a cylindrical sapphire resonator hosted in a gold plated copper cavity. Two coaxial cables protrude inside the cavity exciting the whispering gallery modes of the cylindrical sapphire. The system affords a high quality factor that enables high resolution temperature measurements. This work further develops the principle of the Sapphire Whispering Gallery Thermometer (SWGT) which was developed by Strouse in 2007 [1]. It was shown that a temperature measurement uncertainty of 10 mK was achievable, albeit the sensing device exhibited some mechanical instabilities, especially at temperatures below -20 °C, so that it was not possible to use it as a thermometer without recurrent recalibrations. In this thesis the design of a new WGM resonator is reported. Its mechanical stability was improved so that the temperature working range was extended. Moreover, the quality factor of the new resonator was 90 % higher in comparison to that achieved in the earlier work. This further improved the temperature measurement resolution. The fabricated prototype was investigated in a temperature range from approximately -40 °C to 30 °C, i.e., from the triple point of mercury and the melting point of gallium. A Vector Network Analyzer (VNA) was employed for the resonant frequency estimation and an ASL F900 Precision Thermometry bridge was used for Standard Platinum Resistance Thermometer (SPRT) resistance measurement. Five different whispering gallery modes were investigated in a frequency range spanning from 6 GHz to 14 GHz, however, only the $WGM_{n=5}$ (f = 12.25 GHz) was chosen for temperature sensing because of the good compromise between quality factor and relative sensitivity. A fifth-order polynomial function was used as a calibration curve with sub-millikelvin residuals, approximately one order of magnitude better to that reported in the literature in the same temperature range. Measurement

reproducibility and repeatability were also investigated for such a SWGT thermometer; the estimates are 14 μK and 0.4 mK, respectively. An uncertainty analysis is also reported in this thesis. The calibration procedure generated a combined uncertainty of 3 mK for the device under calibration. Considering the promising results obtained in this work, the SWGT confirms to be a promising alternative to platinum resistance thermometer, both as transfer standard in industrial applications and as interpolating instrument for the dissemination of the kelvin and the temperature scale.

The second microwave device described in this thesis is a sensor-integrated antenna used as sensing node for humidity measurements. The main goal of this research activity was the integration of a relative humidity sensor into a rectangular patch antenna (2.45 GHz) in order to overcome the antenna performance degradation which often occurs during the integration process: the antenna is affected by the presence of the sensor and, at the same time, the sensing performance are affected by the antenna. The main idea was to employ an aperture coupled patch antenna that ensures a weak coupling between the sensing element and the antenna itself. Two Rogers RO4003 substrates were used for this purpose: a patch antenna and a ground plane with aperture in the first substrate; a feedline and a ground plane with aperture in the other substrate. An interdigitated capacitor (IDC) was placed at the end of the feedline and a $BaTiO_3$ – based sensing material was deposited between its fingers. A change in the surface impedance of the deposited material (this is what happens during a water vapour exposure) is transduced into a change on the antenna resonant frequency. The frequency shift was large enough to be recorded, but not so much to detune the antenna out of its working band. Measurements were carried out inside a Thunder Scientific 2500 humidity generator between 10 %rh and 95 %rh in the temperature range from 1°C to 40 °C. The prototype sensing properties and the antenna performances are still under investigation. However, the achieved results show that this device could be used for IoT (Internet of Things) applications or as a sensing node in a Wireless Sensor Network (WSN) for environmental monitoring.