Supplementary material (ESI) for Lab on a Chip

Supplementary Information

Temperature measurement

Most commercial thermocouple thermometers which are used to measure temperatures for PCR applications use a type-k measuring junction with the cold junction replaced by a "cold junction compensator", a semiconductor device which senses ambient temperature and provides an appropriate correction voltage in series with the measurement thermocouple voltage. Such instruments are typically capable of resolving temperatures to ± 0.1°C, but errors, due principally to the cold junction compensator and to a lesser extent the slight non-linearity of the type-k junction temperature characteristic and/or to any linearising circuits intended to correct it, are limited to an accuracy of around ± 1.0°C. In order to meet the measurement requirement for this present application of high accuracy and fast response over a limited temperature range; an alternative means of linearization and cold junction compensation was developed to give an accuracy of ± 0.1ºC over the range 55ºC to 95ºC. The thermocouple amplifier module temperature is stabilized at 50ºC and positioned close to the microwave cavity and a precision platinum resistance thermometer is used to generate the cold junction compensation voltage in order to ensure adequate long-term temperature stability.

To ensure a microwave signal was not superimposed on the low level (around 40 μV/°C) dc signal of a thermocouple the microwave generator was (temporarily) 100% square wave amplitude modulated. The resulting oscilloscope temperature trace showed only the expected triangular heating and cooling waveform, with no step discontinuity occurring at the modulation switching points, thus confirming the adequacy of screening and filtering.

Microwave cavity and power source

The cavity was constructed from a conducting cylindrical copper bar bent into the form of the letter C which will have a resonant frequency. The ends of the bar which are facing each other form a capacitor, and the length of the bar is a single turn coil, an inductor, in series with a capacitor. The structure is therefore able to resonate in a very simple mode as an alternating current travels the length of the bar. It would however be difficult to couple power into such a resonator and troublesome levels of power may be radiated from it.

To topologically develop the resonant bar into a shielded resonant structure it is necessary to envisage the solid created by rotating it 360° about the axis of the capacitor. The resulting structure is a re-entrant quasi-toroidal cavity, from which there can be no radiation emitted. The capacitance value is unchanged, but the inductance is considerably decreased, as it now resembles several single turn inductors in parallel. The resonant mode, and there is effectively only one, has its radio frequency (RF) electric field parallel to the axis of the capacitor formed by the opposing center posts. Because the gap between the posts is small and filled by the glass of the microfluidic device, of dielectric constant around 6, there is little electric field anywhere else. The RF magnetic field runs in the direction of the toroidal cavity space around the posts and is easily excited by a magnetic loop, in our case manufactured from 2.2 mm diameter 50 Ω semi-rigid coaxial cable. The unusual topology of the re-entrant cavity has the advantage in this application of localizing the heating where it is required within a discoidal volume that matches the sample geometry. The design frequency of the cavity was determined partly by the sample chamber diameter and partly by the dielectric absorption characteristic of the glass.

The copper cavity was constructed from identical halves. The re-entrant posts were drilled axially to 1.6 mm diameter for cooling air to impinge straight on to the microfluidic device. Four 0.5 mm wide, 0.5 mm deep grooves were machined in the end of each post so that the glass microfluidic device did not impede air flow; four 1.2 mm holes were drilled in each cavity half for air egress.

A rectangular slot was machined in the side of the cavity opposite the coupling loop to admit the microfluidic device. This could have created an electromagnetic compatibility problem; the slot behaves as a below cut-off dielectric-filled waveguide, the attenuation of which is given in dB/unit length by:

$$\alpha = 8.69\sqrt{\left(\frac{2\pi}{\lambda c}\right)^2 - \varepsilon\left(\frac{2\pi}{\lambda}\right)^2}$$

where λc is the cut-off frequency and ε is the dielectric constant of the glass. The attenuation for the present cavity design is thus over 20 dB, which could be increased simply by increasing the outer diameter of the cavity, but this was not found to be necessary. The resonant wavelength of a re-entrant cylindrical cavity is:

$$\lambda_0 = 2\pi\sqrt{\frac{l\rho_1}{2\delta}\ln\frac{\rho_2}{\rho_1}}$$

where ρ_1 and ρ_2 are the radii of the posts and cavity respectively, l the total post length and δ the gap between the posts. The presence of the microfluidic device decreases the resonant frequency by a factor $\sqrt{\varepsilon}$. As l is short, because there are intrusions into the cavity by the microfluidic device and the coupling loop and because the cavity shape has been made toroidal rather than cylindrical to reduce microwave power loss the calculation is approximate; the resonance was therefore fine-tuned to 8 GHz by incremental machining of the cavity depth.