Dielectric Microwave Resonator for Non-Destructive Evaluation of Moisture and Salinity

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Abstract. A method to measure the moisture and salinity of building materials is the determination of its dielectric properties at Gigahertz frequencies. Using BZT ceramics with a high dielectric constant of about 29, a cylindrical dielectric microwave resonator for nondestructive evaluation of the complex permittivity of building materials was developed. The ceramic cylinder is mounted in a metal container that is open on one side. Coupling loops are placed on opposing sides of the ceramics. With a network analyzer, the resonance frequency, the quality factor and the transmission amplitude are determined. The TE(01δ) resonance, characterized by an azimuthally circulating electrical field and an axial dipolar magnetic field, was found to be very stable. Two resonator setups were realized. In air, resonance frequencies of 1.796 GHz and 2.488 GHz, and quality factors of 15000 and 14000 were measured, respectively. When applying the resonators to the surface of the material under test, the resonance is damped due to the evanescent fringe fields which penetrate 2 to 4 cm deep into the material. The ensuing reduction in the transmitted power and in the quality factor of the resonance is detected. The resonators were calibrated using sand-lime bricks and concrete slabs of defined moisture content and salinity. The measurement results were compared with model calculations using the finite difference program Microwave Studio of CST. The assembly was modeled with different permittivities and loss tangents of the material. The calculated resonances are in good agreement with the experimental findings. It is shown that one can use the measured resonance parameters to deduce the complex permittivity of the material and thus determine its moisture and salinity in the region close to its surface.

1. Introduction

A well known and established method for the non-destructive evaluation of the moisture and salinity of building material is based on the determination of their complex dielectric permittivity in the microwave frequency range from 1 to 10 GHz [1]. For this purpose, a number of measurement techniques are known. Transmission measurements require positioning of the antennas on opposite sides of the building material (see, e.g., the 7 GHz-measurements of Maierhofer *et al.* [2]). Other approaches using two parallel boreholes [3] or a microstrip patch sending antenna outside and a movable dipole detection antenna in a borehole [4] have been reported. Also, the so-called Time Domain Reflectometry using a fork antenna [5] requires two boreholes. In case of one-sided access to the material and no boreholes, the reflectometry technique in the time domain (typically in the 2.45 GHz band) is commonly used [6]. Microwave resonators are preferably used in case the material under test can be inserted in the resonator, e.g. for moisture determination of cigarettes [7]. A one-sided resonator measurement is also possible, however at the expense of reduced penetration depth and loss of information on the depth profile of the moisture distribution.

In order to obtain a high precision of measurement and in order to separate the effects of moisture and salinity, a high quality factor Q of the resonance is required. The realization of open resonators with a high Q is problematic because of the resonance damping by the adjacent moist material. Dielectric resonators on the basis of low-loss microwave ceramics with a high relative dielectric permittivity ε exhibit high quality factors even for partially open geometries. In this paper, an alternative approach for non-destructive moisture and salinity determination is presented [8]. It is based on the observation of the resonant frequency shift and the damping of a high-Q microwave resonator. The principle of operation is explained and supported by numerical simulations of the resonator and the material under test using a Finite Difference Program. The calculated results are compared to measurements of sand-lime bricks and of concrete blocks with variable moisture and salinity.

2. Set-up of dielectric high-Q resonator

For achieving very high quality factors, e.g. for narrow bandwidth filters for mobile phone and satellite communication, dielectric resonators are used. Dielectric resonators on the basis of ceramics with low losses and very high dielectric permittivity ε in the microwave regime yield high quality factors even for partially open resonator geometries. Using Barium Zirconium Titanate (BZT) ceramics with very high relative dielectric permittivities of around 29, cylindrical dielectric microwave resonators were developed for non-destructive determination of moisture and salinity. The resonators are arranged in a cylindrical metal enclosure which is partially open on one side (see Fig. 1).

2.1. Resonator for 1.8 GHz

A cylindrical BZT ceramics with a relative dielectric permittivity of 28 (diameter 30 mm, height 21 mm, central bore 4 mm) is mounted on a PTFE pin which is affixed in the centre of the aluminium cylinder (inner diameter 80 mm, height 41 mm). The resonator is covered by a lid fabricated from 1 mm Teflon foil and a aperture from aluminium (hole diameter 50 mm) in order to increase the quality factor of the resonance. Other apertures with inner diameters of 55 mm, 60 mm and 65 mm were also tested. They yielded a broader resonance and were thus less sensitive. Therefore, the 50 mm aperture was used in the subsequent experiments. On opposite sides of the resonator ceramics, coaxial transmission lines are guided into the aluminium casing. They are terminated with a coupling loop of 3 mm diameter such that the area vectors are parallel to the symmetry axis of the resonator. The loops are used to couple the rf signal into and out of the resonator.

2.2. Resonator for 2.45 GHz

For the 2.45 GHz resonator, a cylindrical BZT ceramics with a relative dielectric permittivity of 29.5 (diameter 21.5 mm; height 15 mm) is used. The resonator rests in a 2 mm deep bore of a PTFE cylinder with an outer diameter of 24 mm and a height of17 mm, which is mounted in the centre of a cylindrical aluminium casing (inner diameter 58 mm, height 33 mm, aperture dia. 40 mm). The resonator is covered with a thin lid of PTFE (1 mm).

2.3. Readout with a network analyser

Via the coaxial lines, the resonator is connected to the reflection and the transmission port of an vectorial network analyser (Hewlett Packard 8752A). The transmission was measured in the frequency range around the resonance frequencies of the resonators. The resonance frequencies and quality factors in air (without building material) were found to be at 1795.95 MHz with a Q = 15000 for the 30 mm diameter resonator and 2488.02 MHz with a Q = 14000 for the 21.5 mm diameter resonator. Using the marker functions of the analyser, the centre frequency of the resonance, the –3 dB width of the peak and the resultant quality factor Q and the insertion loss at the resonance were recorded automatically.

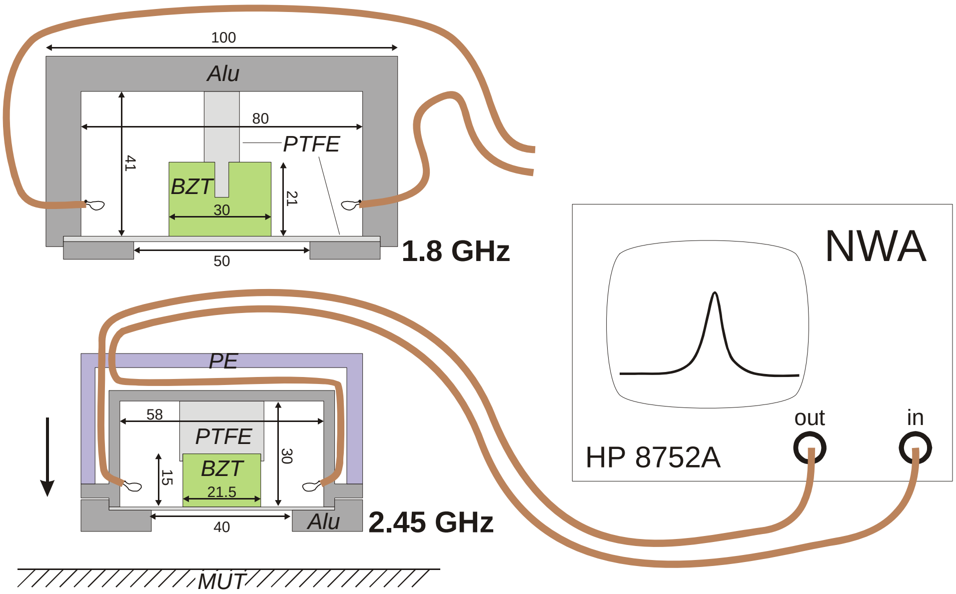

Fig. 1. Sketch of the 1.8 GHz and the 2.45 GHz dielectric resonators and their readout with a network analyser (NWA). The dielectric BZT ceramics is fixed by PTFE supports in an Aluminium casing with a PTFE lid. The resonator is pressed with its aperture side on the material under test (MUT) for performing a measurement.

3. Simulations using the finite difference program Microwave Studio from CST

Using the finite difference program “Microwave Studio” from CST, the system comprising of the dielectric resonator and of the building material under test was simulated for different complex values of the dielectric permittivity of the material. The material was modelled as a cylindrical shape with a diameter of 110 mm – 120 mm, a height of 46 mm – 56 mm and with variable real and imaginary permittivity. Free boundary conditions were assumed for the material. The aluminium enclosure was modelled as „Perfectly Electrically Conducting“ (PEC) with the dimensions according to Fig.1 . The materials were discretized with 15000 – 46000 nodes. For each set of parameters of the building material, the Eigen frequencies of the dominant modes were determined using the Eigenmode Solver of the simulation program. From the calculated Eigen modes, the $TE_{01\delta}$ resonance was selected, which was found near 1.8 GHz or 2.48 GHz, respectively. This mode is clearly identifiable since it is characterized by an azimuthally circulating E field and an axial dipolar H field.

Fig. 2 shows the calculated electrical field in the resonator and in the material under test as a cross-sectional contour plot of the component of the electrical field which is perpendicular to the cutting plane. It can be seen that the electrical field penetrates up to about 4 cm deep into the material under test. The magnetic field H looks like the field from a solenoid in the form of the cylindrical surface of the BZT ceramics. With aperture, this penetration depth reduces to about 2 cm.

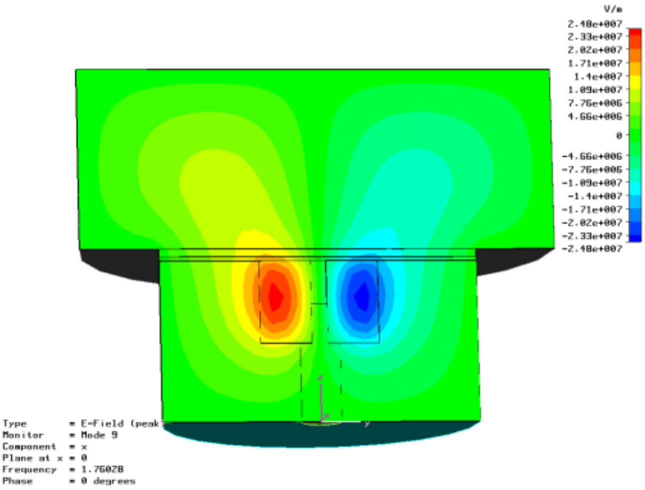

Fig. 2. Simulated electric field of the $TE_{01\delta}$ mode of the cylindrical dielectric resonator without aperture in the y-z plane. The x component perpendicular to the plane is displayed.

Using the perturbation theory solver, the losses were calculated under the assumption of realistic electrical conductivity for the aluminium and loss tangent $\tan\delta = \mathrm{Re}(\varepsilon)/\mathrm{Im}(\varepsilon)$ of the material under test, see Fig. 3.

For determining the effective dielectric constant of systems which consist of a mixture of several phases, several models have been developed [9]. In the case of moist porous building material, one would consider three phases, namely the dry porous material, water and air. According to Schlemm [10], the Complex Refractive Index (CRI) model is well suited to describe different porous building materials, especially lime bricks, sand lime bricks and clay bricks. This model describes the complex refractive index $\sqrt{\varepsilon}$ of the material as the weighed sum of the volume fractions of the refractive indices of the constituents. For the relationship between moisture and the dielectric permittivity Re(ε) at 2.4 GHz, the formulas for porous building material according to Schlemm [10] were used.

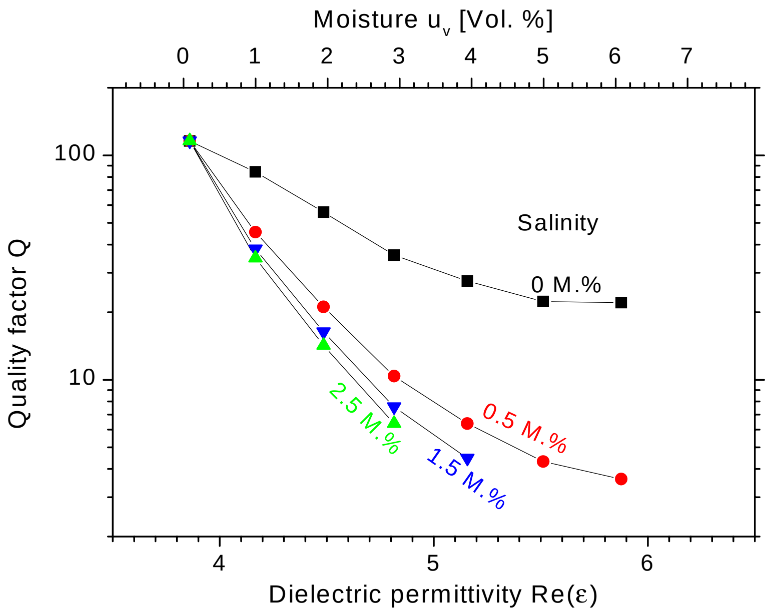

Fig. 3. Vector plot of the simulated magnetic field of the $TE_{01\delta}$ mode of the semi-open dielectric high-Q resonator (without aperture).

The results of the simulations give a clear picture about the resonant mode that is excited in the resonator. The frequency shift and the reduction of the quality factor of the resonance with increasing moisture and increasing salinity are clearly observed in the simulated data. We also performed simulations of the exact geometrical structures of our resonators. However, we did not get the high quality factors in the simulations that were measured experimentally. We assume that this is due to our limited mesh accuracy. With a refined mesh with significantly higher number of nodes, it is expected that quantitatively reliable results can be obtained, hovewer at the expense of long computation time.

4. Measurements of sand-lime bricks

4.1. Preparation of the sand-lime brick samples with defined moisture and salinity

As a reference building material, typical standard sand-lime bricks with dimensions of 240 mm × 114 mm × 113 mm were used. They were put into an exsiccator which was evacuated using a rotary pump for three days. The dry density of the brick was determined to be 1.89 g/cm^3. Then, the exsiccator was flooded with water. From the difference in weight, a maximum water sorption of 25.5 Vol.% was found. Subsequently, the bricks were left in ambient laboratory environment for drying. Over a period of 14 days, the bricks were regularly weighed and measured by putting the dielectric resonators on their flat surface. The measurement was performed by simply pressing the dielectric resonator at the brick’s surface and recording the resonance frequency shift, the reduction of the quality factor and the transmission loss.

Finally, the sand-lime bricks were vacuum-dried again and flooded with salt water. For this purpose, NaCl (purity 99.5%) was dissolved in water. The salinity per unit mass of the sand-lime bricks was determined from the maximum water sorption and the percentage of salt in the water. This value was found to be in good agreement with the increase in mass which was measured by weighing the brick again after drying.

4.2. Measurements with the 1.8 GHz resonator

The sand-lime bricks were measured with the 1.8 GHz resonator. The results for the resonance frequency f_0 and the quality factor Q as a function of the water content in Vol. % are graphically displayed in Figs. 4 and 5.

The experimental values were approximated using polynomial fitting curves. For the resonant frequency as a function of the salinity and the quality factor, the approximation (1) was chosen. For the quality factor as a function of moisture and salinity, Eq. (2) was selected. The fitting parameters *A*, *B*, *C*, *D*, *E*, *F*, and *G* of the multi-parameter fit are listed in Table I:

$$f_0(Q)\,[\mathrm{MHz}] = A + \frac{B + C\cdot\sqrt{s_m}\;[\mathrm{M.\%}]}{(\log_{10} Q)^4} + \cdot\frac{D}{(\log_{10} Q)^6} \tag{1}$$

$$\log_{10} Q = E\cdot\left(1 - \frac{u_v\,[\mathrm{Vol.\%}]}{24\%}\right)^{1+F\cdot s_m[\mathrm{M.\%}]} + G \tag{2}$$

Table I. Fitting parameters for the analytical expressions for the resonance frequency f_0 and the quality factor Q of the dielectric 2.45 GHz resonator as a function of moisture u_v and salinity s_m.

A	*B*	*C*	*D*	*E*	*F*	*G*
1796.5	-433.64	100.66	1390	1.4546	1.2676	1.8986

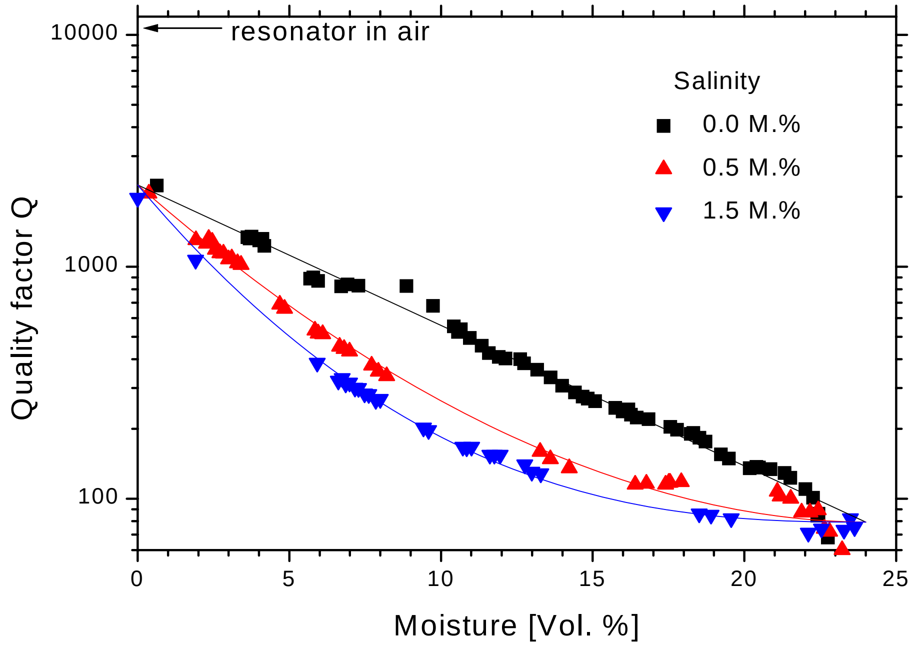

Fig. 4. Measured quality factor of the resonance of the dielectric 1.8 GHz resonator as a function of the moisture of the sand-lime brick under test, for different salinities. The lines denote the polynomial fits Q to the data according to Eq. (2), see text.

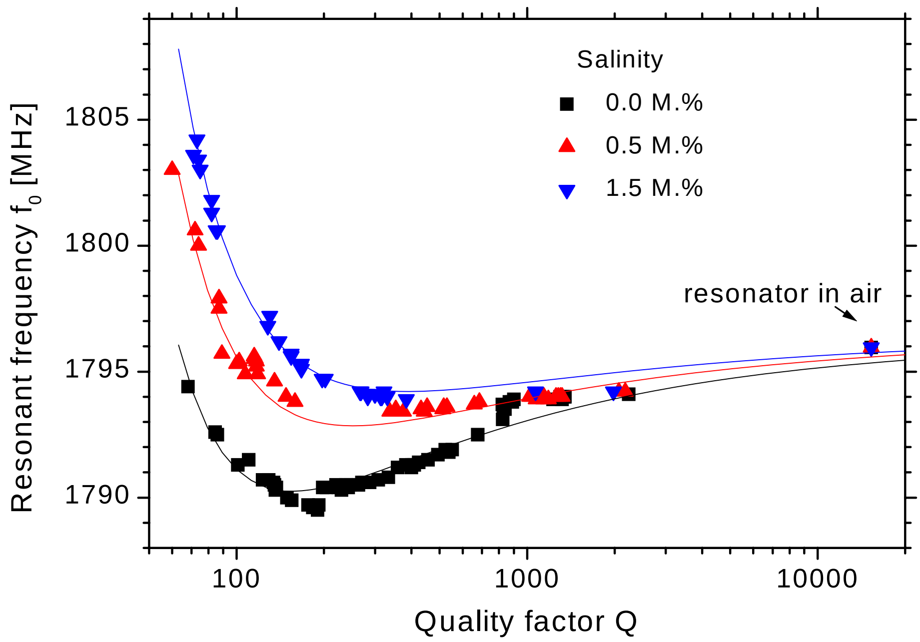

Fig. 5. Measured resonance frequency of the dielectric 1.8 GHz resonator as a function of the quality factor of the sand-lime brick under test, for different salinities. The lines denote the polynomial fits f_0 to the data according to Eq. (1), see text.

Using the analytical formulas for the quality factor Q and the resonance frequency f_0 of the dielectric 1.8 GHz resonator, contour lines of constant moisture and of constant salinity were calculated. The resultant parameter field with the equi-moist and equi-salt lines is displayed in Fig. 6. From the fact that the lines of constant moisture and constant salinity span a broad parameter field, except in the limit of very dry material, it can be deduced that moisture and salinity may be independently determined from measurements with the 1.8 GHz resonator.

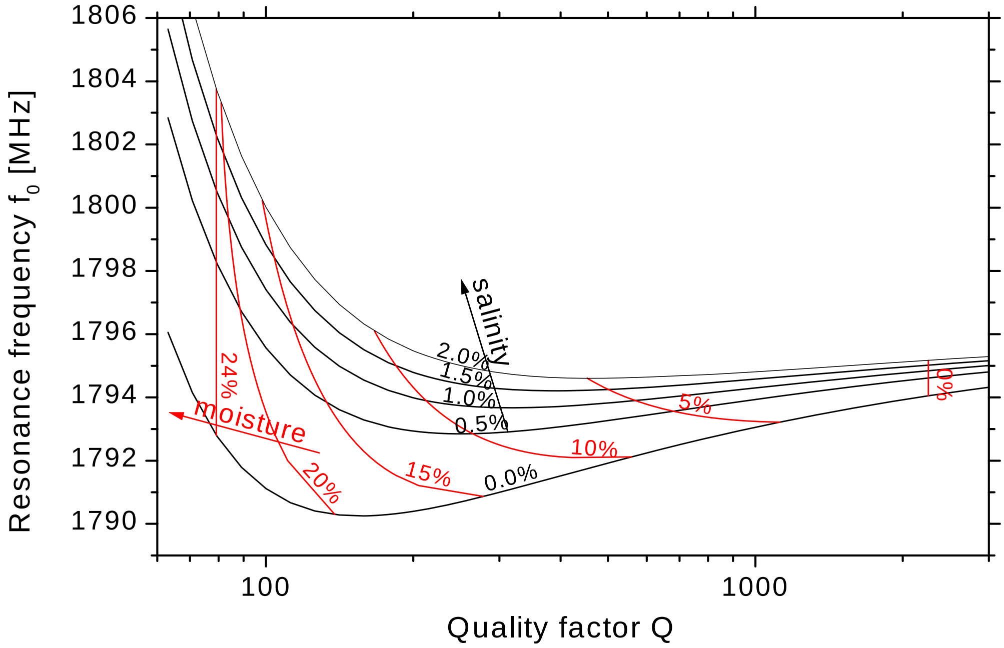

Fig. 6. Contours of constant moisture and of constant salinity in a graphical representation of the resonant frequency and the quality factor of the resonance of the dielectric 1.8 GHz resonator.

Thus, the moisture and salinity of unknown material under test may be determined by entering the measured pair of values f_0 and Q into Fig. 6 and interpolating the water and salt content from the neighboring lines. It is also possible to invert Eqs. (1) and (2) numerically to obtain values for the moisture u_v and the salinity s_m of the sample.

4.3. Measurements with the 2.45 GHz resonator

In analogy to the examinations described above, sand-lime bricks were regularly weighed and measured with the 2.45 GHz resonator during the drying period of several weeks. The measured results for the resonance frequency f_0 and the quality factor Q as a function of the water content in Vol. % are graphically displayed in Figs. 7 and 8.

In order to obtain a formula for the resonance frequency and the quality factor as a function of moisture and salinity, a multi-parameter fit was performed on the measured data using the following analytical expressions. The fitting parameters are listed in Table II.

$$f_0[\mathrm{MHz}] = a - (b - c \cdot s_m[\mathrm{M.\,\%}]) \cdot u_v^2[\mathrm{Vol.\,\%}] \tag{3}$$

$$\log_{10} Q = (d - e \cdot s_m[\mathrm{M.\,\%}]) \cdot \left(\frac{u_v[\mathrm{Vol.\,\%}]}{100} - f \right)^2 + g \tag{4}$$

Table II. Fitting parameters for the analytical expressions for the resonance frequency f_0 and the quality factor Q of the dielectric 2.45 GHz resonator as a function of moisture u_v and salinity s_m.

a	*b*	*c*	*d*	*e*	*f*	*g*
2486.6	0.01045	0.00251	8.4334	2.1627	0.4403	1.8734

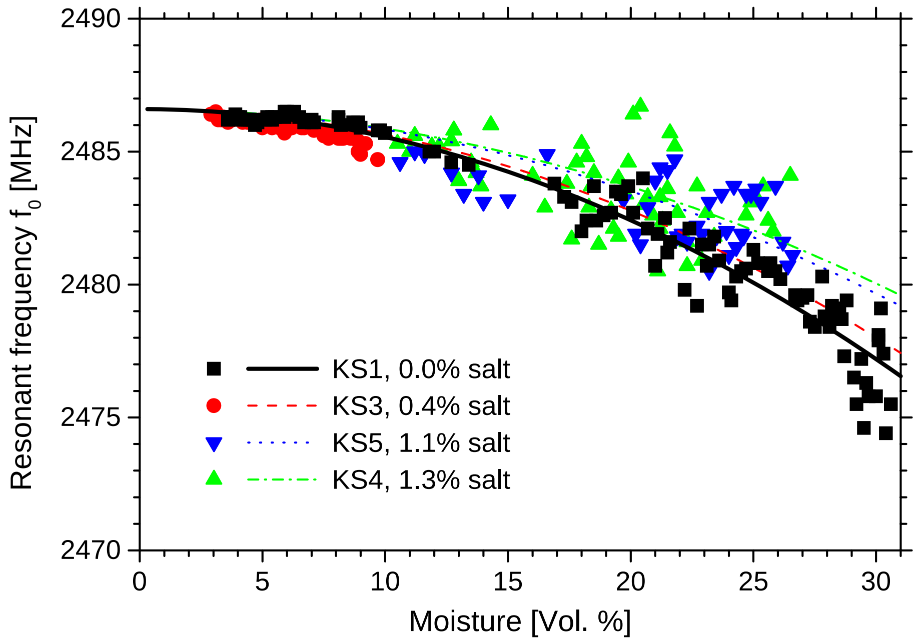

Fig. 7. Measured resonance frequency of the dielectric 2.45 GHz resonator as a function of the moisture of the sand-lime brick under test, for four different salinities. The lines denote polynomial fits f_0 to the data according to Eq. (3), see text.

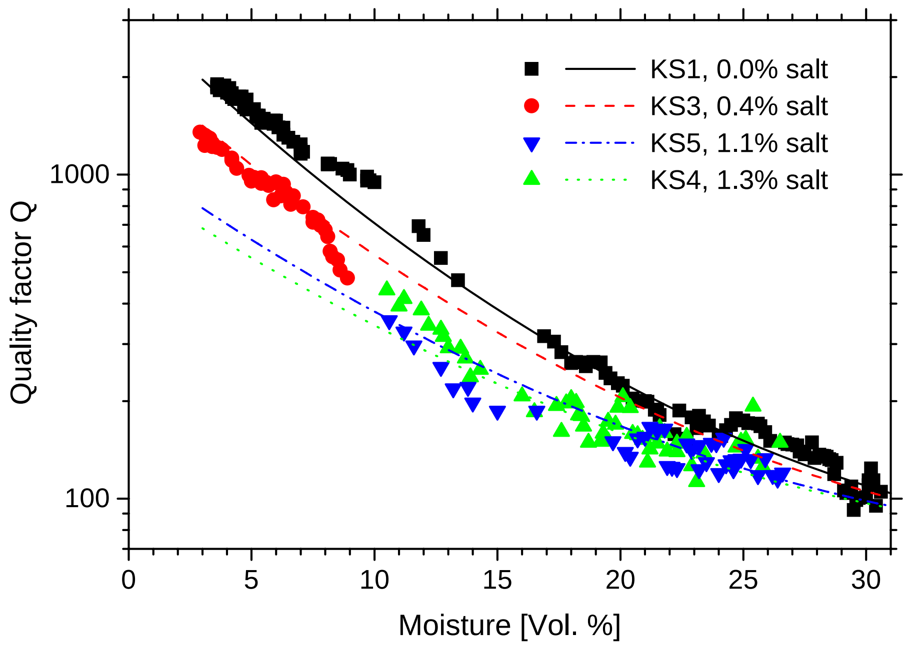

Fig. 8. Measured quality factor of the resonance of the dielectric 2.45 GHz resonator as a function of the moisture of the sand-lime brick under test, for four different salinities. The lines denote the polynomial fits Q to the data according to Eq. (4), see text.

With these analytical representations for the resonance frequency f_0 and the quality factor Q of the dielectric 2.45 GHz resonator, contours of constant moisture and constant salinity were calculated and plotted in Fig. 9. It can be easily seen that the effects of moisture and salinity are clearly separable also for this resonator, except in the limiting case of very dry material.

Thus, the moisture and salinity of unknown material under test may be determined either by plotting the pair of measured values f_0 and Q into this graph or by solving the equations (3) and (4) numerically for u_v and s_m.

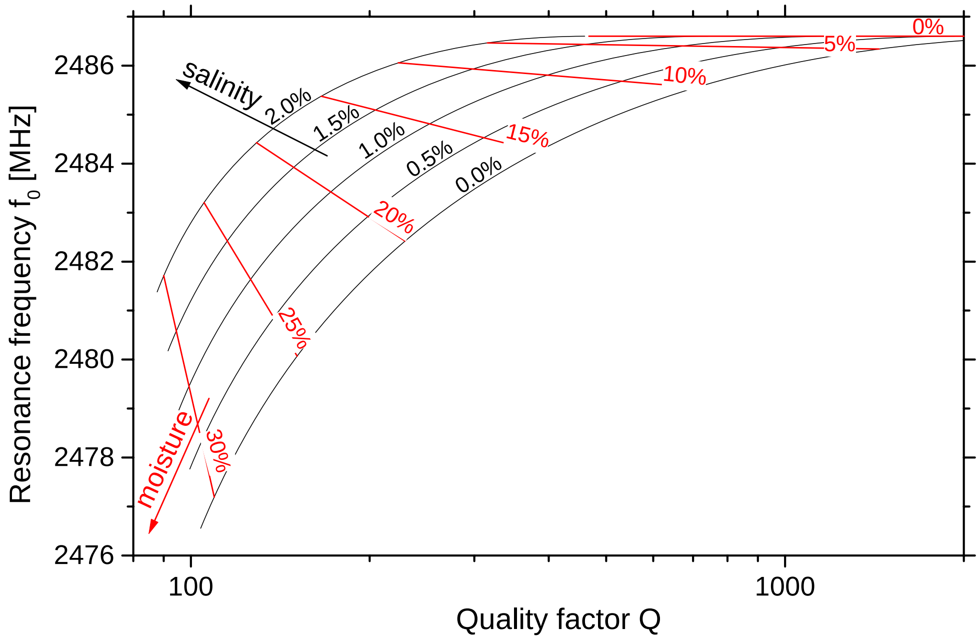

Fig. 9. Contours of constant moisture and of constant salinity in a graphical representation of the resonant frequency and the quality factor of the resonance of the dielectric 2.45 GHz resonator.

5. Measurements of concrete blocks

The measurements were performed in analogy to the measurements of sand-lime bricks, using both the 1.8 GHz resonator and the 2.45 GHz resonator.

The concrete block samples (cubes with a size of 10 cm × 10 cm × 10 cm and cylinders with 15 cm diameter and 10 cm height) were prepared with a water / cement value of w/z = 0.7 in order to obtain a porous concrete with a high water absorption capability. The samples were vacuum-dried for about one week. At the end of the week, their mass remained almost constant with time. Then, the exsiccator was flooded with water. The concrete blocks achieved water saturation percentages of 12.7 Vol.% (#1), 17.5 Vol.% (#4), 15.7 Vol.% (#5), 21.0 Vol.% (#15) and 11.6 Vol.% (#18). They were dried in ambient laboratory environment. Their moisture content was determined regularly by weighing the samples for up to 85 days. The results of the resonator measurements as a function of the moisture content are depicted in the following figures.

Subsequently, two concrete blocks (#4 and #18) were vacuum-dried again and flooded with salt water. For this purpose, different amounts of NaCl (purity 99.5%) were solved in water. The salinity per unit mass of the concrete was determined from the maximum water sorption and the percentage of salt in the water. Values of 0.6 M.% and 0.8 M.% were found.

The following Figures 10 and 11 show the results of the resonator measurements at the concrete blocks. For comparison, the fitting results f_0 and Q according to Eqs. (1) to (4) for the sand-lime bricks are also shown as thin solid lines.

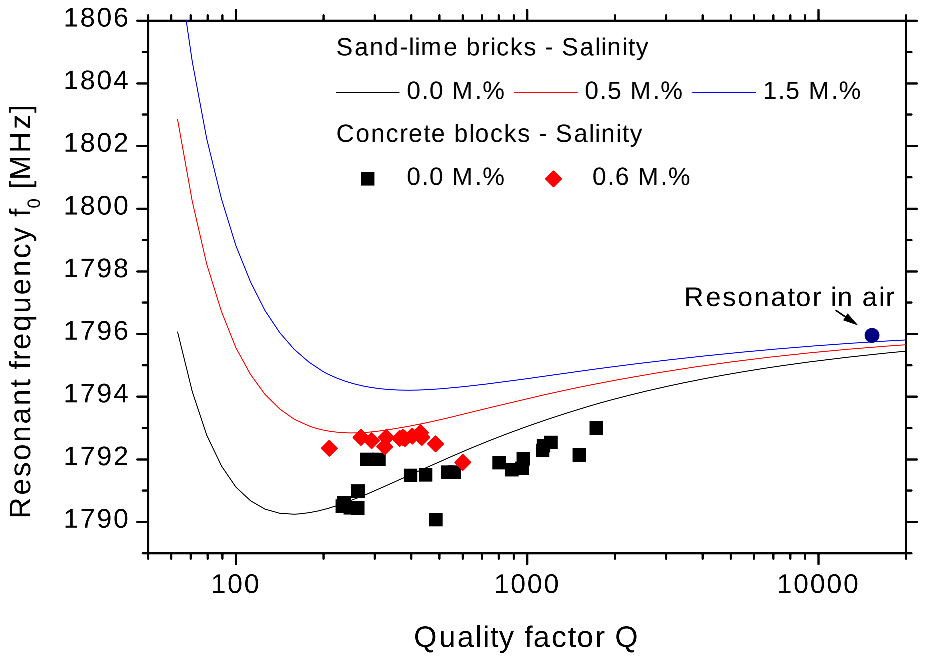

Fig. 10. Measured quality factor Q and resonance frequency f_0 of concrete blocks of different salinity. The data were measured with the 1.8 GHz resonator at different times during the drying period (variable moisture). For comparison, the contours of constant salinity are also given.

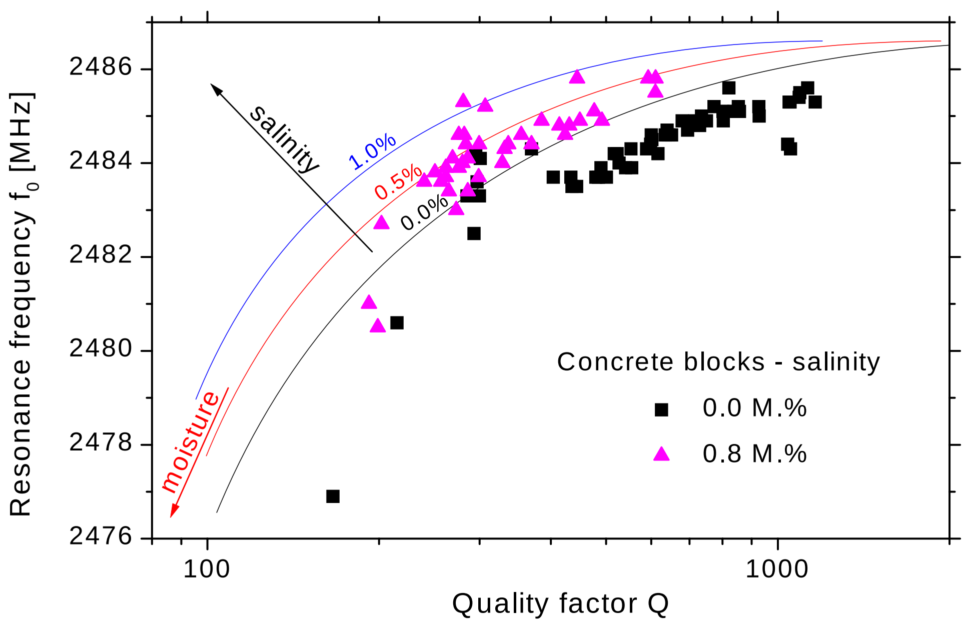

Fig. 11. Measured quality factor Q and resonance frequency f_0 of concrete blocks of different salinity, measured with the 2.45 GHz resonator during drying. For comparison, the contours of constant salinity are drawn as thin lines.

In the measurements of the concrete blocks, a significantly wider spread of experimental values was found as compared to the sand-lime brick measurements. The values measured with the concrete blocks with salt (red symbols in Fig. 10, magenta in Fig. 11) can be discerned from the values of samples without salt (black symbols). However, the reliability of a single measurement is limited. The observed larger errors in the experimental values for concrete in comparison to sand-lime brick are not unexpected. They may be attributed to the rather inhomogeneous structure of concrete. In contrast, sand-lime bricks are very homogeneous.

6. Conclusion and outlook

Based on high-Q dielectric microwave resonators, a novel technique and set-up for the non-destructive determination of the moisture and salinity of building materials was developed. The frequency shift and the damping of the resonator is evaluated when the resonator is being brought close to the material under test.

Two resonators were set up, one for 1.8 GHz and one for 2.45 GHz. The resonators consist of a cylindrical BZT ceramics with a very high dielectric constant, mounted in a semi-open aluminium casing and covered by an aluminium aperture. The $TE_{01\delta}$ resonance modes of the resonators in air were observed at 1.796 GHz and 2.488 GHz, respectively. The $TE_{01\delta}$ mode, which is characterized by an azimuthally circulating E field and an axial dipolar H field, was found to be very stable. In air, –3 dB quality factors of 15000 and 14000 were measured. Upon placement of the resonator on the planar surface of building material under test, the evanescent electromagnetic fields of the $TE_{01\delta}$ mode are altered. These so-called „fringe fields“ penetrate the material by 2 to 4 cm. They penetrate the lesser the moister the material is. The moisture and salinity readings are integral values over this depth range. It is not possible to record a depth profile of the moisture. The ensuing reduction in the quality factor of the resonance occurs without significant radiation losses such that the resonant mode remains clearly observable even for very wet materials. Thus, the resonators exhibits a very large measurable range of moisture.

Experimentally, calibration curves for sand-lime bricks with different moisture and salinity were recorded. It was found that moisture and salinity influence the resonance frequency and the quality factor differently but in a well-defined way. The results were fitted to calibration curves. With the help of these curves, the moisture and the salinity of an unknown material under test may be determined independently, provided that the material is not too dry.

In the case of concrete block samples, a larger spread of experimental values was observed. This variation is due to the inhomogeneous structure of concrete. Consequently, the error will be much larger in the case of concrete.

By means of finite difference simulations of the resonator and the building material, the resonant behaviour could be reproduced theoretically. The calculated frequency and quality factor were found in good qualitative agreement with the experimental findings.

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