8 Microwave and RF Resonator-Based Aquametry

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8.1 Introduction

Among known measurement methods used for determination of various nonelectrical quantities, certain advantages are inherent to radiofrequency (RF) and microwave techniques [1–14]. RF and microwave methods are most widely used for measurement of water content in various liquid, gaseous, particulate and solid substances. Such methods-based moisture and humidity measuring devices are very high sensitive to water content in the appropriate frequency bands and provide possibilities of accurate metering, contactless and averaged through measuring volume measurements. Theory and applications of known RF and microwave moisture/humidity measuring devices are contained in numerous publications (monographs [1–7], papers, patents). Certain RF/microwave resonator-based moisture/humidity meters are proven to be very effective devices. Because physical processes in moist materials are described in said publications in detail, here will we considered principles of design and some applications of known and new RF and microwave resonator-based sensors and measuring devices for water content determination in various substances.

8.2 Traditional and New Types of Resonator Sensors and some of their Applications for Microwave and RF Aquametry

8.2.1 Basic Types of Resonator-Based Moisture/Humidity Sensors

Microwave measurement methods imply the use of various transmission lines, resonators, and radiating elements as sensors. They provide accurate contact and distant measurements. A variety of RF and microwave resonator sensors exist. Multiple constructions of traditional RF/microwave resonator sensors are suggested for aquametry. They are built from basic RF/microwave components or modified and used as sensors. The latter are specially constructed for the solution of definite measuring tasks. The oscillation characteristics (resonance frequency f, quality factor Q) of a resonator sensor are changed depending upon the moisture/humidity of a substance in the electromagnetic field of such a resonator. A moist substance can be placed within a RF or microwave (coaxial, two-wire, stripline, cavity, etc.) resonator, outside it in the fringing field or in some other way in order to provide interaction with the electromagnetic field and thus change the value of a sensor parameter (f, Q). Such sensors for resonator aquametry are described in the literature (for instance, in monographs [1–7]).

8.2.2 New Types of Resonator Sensors and some of their Applications in Aquametry

On-line determination of water content in various liquid, solid, gas and particulate substances is needed in many industrial applications. Microwave sensors are considered effective for contactless moisture measurement of substances in stationary conditions, transported on conveyor belts, or in pipelines [1–7]. However their sensitivity to moisture and/or measurement accuracy are not enough in some applications. Besides, if non-homogeneous moist gas, liquid, particulate substances are monitored, in many cases known sensors don't provide independent measurement results for the random distribution of these non-homogeneities. In tasks where the position of a monitored moist object is not stable, which is often true for production of sheet-like (paper, etc.) materials, then the output characteristics of known microwave sensors used for such purposes are dependent on this disturbing factor, resulting in a decrease of measurement accuracy. New principles for microwave sensor design are considered here, which allow us to realize sensors without the above drawbacks.

8.2.2.1 Waveguide-Based Resonators with Separate Interaction of Oppositely-Directed Waves with Moist Substances

Waveguide resonators are used in particular as sensing elements in traditional microwave resonator aquametry. A monitored object is located in such a sensor in the standing wave field disturbing initial electromagnetic field distribution. However in some applications principally achievable measurement accuracy or/and sensor sensitivity are non-satisfactory. These drawbacks result from nonuniform field distribution along the resonator length: the position of a monitored object in the resonator field is not often exactly known or may change during monitoring process.

Possible methods for the design of microwave sensors are considered here, as well as measuring devices based on them that give ability to solve the listed problems. They have higher sensitivity or/and accuracy compared with existent ones. Design of the considered microwave resonator sensors can be realized using passive microwave components for controlling the propagation characteristics of guided electromagnetic waves (direction of propagation, amplitude, phase, polarization) and, as a result, of sensor output characteristics. Advantages of such sensors are: improved measurement accuracy; increased sensitivity to measured moisture/humidity; invariance of measuring results to the influence of different disturbances. For the control of sensor output characteristics, various functional microwave components (circulators, directional couplers, phase shifters, etc.) can be applied. These microwave components, as well as waveguides, are designed and manufactured for the use in certain, rather broad frequency bands.

With the proposed microwave techniques, significant improvement of functional characteristics (measurement accuracy, sensor sensitivity) as compared with existent analogous ones can be realized. The improvements are achievable due to the design of these sensors on the base of waveguide-based resonators where *separate* interaction of oppositely-directed travelling electromagnetic waves with monitored moist substances takes place.

In such sensors are performed the following functions: interaction of only one-directed travelling wave with a monitored object; said interaction of both such waves separately; different degree of propagation characteristics change for oppositely directed waves under said interaction. Phase shifts of waves in such sensors determine values of informative parameters that can be much more sensitive to measured quantities, in particular to moisture/humidity. In order to provide said interaction of waves with an object at least one non-reciprocal component (circulator, directional coupler) is introduced into the sensor construction. Similar schemes may also be listed for separate interaction of both oppositely-directed waves. For contactless (on-line) measurements, the proposed waveguide/resonator sensors contain aerial antennae. Some of the schemes listed above are considered here in detail and are described for measurement of moisture. Examples of schemes for certain applications based on similar approaches are presented in [15].

The appropriate interaction schemes are considered here using initially linear waveguide resonators (Fig. 8.1). A monitored object is sounded separately at least by one of the oppositely-directed travelling waves.

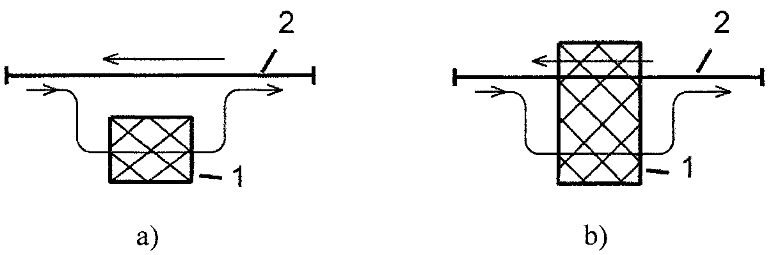

Fig. 8.1. Schemes for separate one-direction (**a**) and two-direction (**b**) interaction of waves in waveguide resonator with a monitored object (examples)
1 – monitored object, *2* – initial waveguide resonator

For the provision of wave–object interaction at least one of the oppositely-directed waves is lead out from the resonator and returned there again after the completion of such an interaction; Fig. 8.1a shows such a scheme for a single path interaction. Object 1 is a dielectric one, possibly with losses; multiple interactions of waves with objects in such schemes are also possible; there can be various modifications of these interaction schemes depending on the tasks to be solved. Also, separate interaction of both oppositely directed waves with an object 1 is possible (Fig. 8.1b).

In general, using microwave scheme components allows the behavior of each of the oppositely-directed waves to be controlled. In particular, both the waves that are initially oppositely-directed may be guided in one direction, providing nevertheless their separate interaction with a monitored object.

Resonator devices with controlling passive components for guided waves may be designed according to the wave–object interaction schemes in Fig. 8.1. They are applicable for on-line moisture determination. Here we consider only some examples of such devices. Figure 8.2a shows the scheme of the device that corresponds to the interaction scheme in Fig. 8.1a. A moist substance 1 is sounded by travelling, one-direction waves excited in the waveguide resonator. Three-port circulators 3 are used for the provision of such a sounding. They are installed into the waveguide 2 along its length. One of them (left) is used for leading one of the oppositely-directed waves out of the resonator while the other one (right) is used for input of the wave again into the resonator after interaction with the substance. In particular, radiating (left) and receiving (right) antennas 4 are used as sensitive elements. The resonator is formed here by the plurality of microwave components: resonator, circulators, the other parts of wave trajectories containing the sensitive elements. Oscillator 5 is connected to the resonator; electronic unit 6 is used for measurement of resonance frequency. Waves reflected from surfaces of a substance 1 and propagating at the opposite direction, don't really influence measurement results. They circulate within the ring circuit restricted by circulators. Such a scheme provides measurement results independent of position and/or sizes of a substance relative to antennas.

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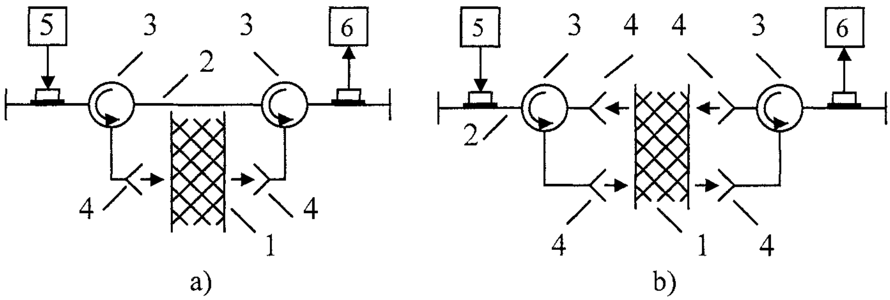

Fig. 8.2. Schemes of microwave measuring devices with separate one-direction (**a**) and two-direction (**b**) wave–object interaction (examples)
1 – monitored object, *2* – waveguide, *3* – circulator, *4* - antenna, *5* – oscillator, *6* – measuring unit

The scheme of the microwave device corresponding to the interaction scheme in Fig. 8.1b is shown in Fig. 8.2b. A moist substance 1 is probed separately by both oppositely-directed waves in the resonator. Wave–object interaction is realized with the application of sensitive elements that are two pairs of transmitting and receiving antennas 4. Also other types of sensitive elements may be applied. The direction of the wave propagation is shown by arrows. Two circulators 3 serve for provision of separate interaction of travelling waves with an object 1. Like the scheme in Fig. 8.2a, here also waves reflected from the surfaces of a moist substance 1 really don't influence the measurement results. These waves circulate in the opposite direction within the circuit restricted by circulators. Such a scheme, being similar to the scheme in Fig. 8.2a, is characterized by twice sensitivity to a measured quantity. The position of an object between antennas in the direction of sounding doesn't influence the measurement results.

The natural (resonance) frequencies of the synthesized resonator are determined by phase relationships according to trajectories of waves, as well as by other characteristics of guided waves, and by the dielectric/geometrical parameters of moist substances.

The resonator structures considered above are neither more linear nor more ring-shaped than previously examined structures. Instead of them there exist now more complicated resonator structures. They may be called linear-ring resonators.

The described schemes of wave–object interaction in a waveguide resonator allow broader application areas for microwave sensors because of the possibility of contactless measurements, and the increase of sensitivity using multiple soundings of an object separately by one and both of the oppositely-directed waves. By varying scheme parameters and choosing an informative parameter, these schemes may be optimized taking into account the specifics of a solved measurement problem and the needed sensitivity. In particular the natural (resonance) frequency of oscillations may be chosen as the informative parameter of a microwave sensor.

Resonance Frequencies Versus Parameters of Monitored Objects

The resonance frequencies of resonator sensors can be used as informative parameters. Their values can be estimated using a simplified approach assuming TEM-approximation – free-space propagation of transverse electromagnetic (TEM) waves and position of a monitored object in designed resonators.

The natural (resonance) frequencies of the synthesized resonator are determined by phase relationships according to the trajectories of wave propagation, by other characteristics of guided waves, and by dielectric/geometrical parameters of moist substances.

The scheme in Fig. 8.1a is considered as an example (other schemes can be described in a similar way). For this case the following relationship for resonance conditions can be written:

$$\beta_0(2l - \Delta l + l_s - l_m) + \beta\, l_m = 2\pi n \qquad n = 1, 2, \ldots \qquad (8.1)$$

where β_0 is the propagation factor for waves in the initial resonator 2 and in a path (free-space, waveguides) outside it; for simplification it is assumed that its value is the same in the designed resonator: for a free-space path $\beta_0 = 2\pi f_r (\varepsilon_w)^{1/2}/c$, for a waveguide path $\beta_0 = 2\pi[\varepsilon_w - (f_c / f_r)^2]^{1/2} / c$, where f_r and f_c are resonance frequency and cut-off frequency in the waveguides, respectively, ε_w is relative dielectric permittivity of a substance in a wave pathway (free-space, waveguides) , c is velocity of light; $\beta = 2\pi f_r [\mathrm{Re}(\varepsilon_m(W)]^{1/2} / c$ is propagation factor in a monitored substance 1 with moisture W; l is the length of the initial resonator 2; Δl is the length of the part of the resonator 2 between points of leading waves out of this resonator and introducing them into it again; l_s is sum length of waveguide pathway outside of the initial resonator; l_m is pathway length of waves in a substance 1; ε_m is relative dielectric permittivity of a substance 1.

For lossy dielectrics

$$\varepsilon_m = \varepsilon_m' + j(\varepsilon_m'' + \frac{\sigma_m}{2\pi f \varepsilon_0}) \tag{8.2}$$

where ε_m' and ε_m'' are the real and imaginary parts of ε_m. The value of ε_m'' corresponds to dielectric losses due to displacement currents, σ_m is conductivity of a substance; f is frequency; ε_0 is permittivity of vacuum (8.85×10^{-12} F/m).

From Eq. (8.1) follows the expression for natural (resonance) frequency f_r, assuming free-space wave propagation ($f_c = 0$):

$$f_r = \frac{nc}{(2l - \Delta l + l_s - l_m)\sqrt{\varepsilon_w} + l_m(\mathrm{Re}\langle\sqrt{\varepsilon_m}\rangle)}, \quad n = 1,2,... \tag{8.3}$$

By measuring f_r, the value of ε_m and W may be determined. From Eq. (8.3) it follows the formula for the change of frequency f_r relative to its initial value f_{r0} follows:

$$\frac{\Delta f_r(W)}{f_{r_0}} = \frac{f_r(W) - f_{r_0}}{f_{r_0}} = -\frac{l_m(\mathrm{Re}\langle\sqrt{\varepsilon_m}\rangle)}{nc} f_r(W) \tag{8.4}$$

here f_{r0} is initial (at $l_m = 0$ or $\varepsilon_m = \varepsilon_w$) value of f_r (W).

The following data can be used in Eq. (8.3) as a numerical example of the scheme considered: $l = 20$ cm, $\Delta l = 10$ cm, $l_s = 20$ cm, $l_m = 10$ cm, $\varepsilon_w = 1$, $\varepsilon_m = 2$. Then it follows: $f_r = 0.6n$ GHz. So if $n = 5$ then $f_r = 3.0$ GHz. For the change of ε_m to the value $\varepsilon_m = 2{,}5$ due to water content, the corresponding relative change of f_r is $\Delta f_r/f_r = 1.63$ (%). Such a change of ε_m corresponds to the range $W = 0 - 8.3$ % if water content in oil or oil products (with $\varepsilon_m = 2$ at $W = 0$) is determined.

8.2.2.2 RF TEM Line-Based Resonator Sensors

Devices based on RF sensors are rather simple and cost-effective to implement [1]. They are effectively used for the measurement of various technological parameters. In particular RF sensors are applicable in the building industry [16, 17]. RF resonator sensors for contactless characterization of various materials can be synthesized on the base of specially designed sections of two-wire lines, strip-lines, etc. Specifically, elements of technological installations may be effectively used as RF sensors.

Lattices of metal rollers are used in some installations for conveying manufactured items. Such a lattice is shown in Fig. 8.3. Two neighboring rollers 1 and 2 isolated from others may be considered as a two-wire TEM transmission line. Being short-circuited on both ends such a construction represents a RF resonator that is a half-wave TEM-line section.

Water content in a material on the lattice can be determined by exciting electromagnetic oscillations in this line section and measuring the value of an informative parameter (resonance frequency, quality factor). Consider the following lattice for transportation of clay mass in the production of bricks: distance between rollers 50 mm, length of a roller 400 mm, total length of the table with rollers 600 mm, its height 800 mm. Contactless coupling elements may be placed at the short-circuited ends of the line section in order to excite electromagnetic oscillations and receive information for further processing.

If resonance frequency f_r is used as informative parameter for determination of water content W, then

$$f_r = \frac{cn}{2l\sqrt{\varepsilon_{eff_0}}} \tag{8.5}$$

where c is speed of light, l is length of a roller, $n = 1,2, \ldots$ is number of harmonics excited in the resonator, $\varepsilon_{\mathrm{eff}\,0}$ is effective dielectric permittivity of two-layered (air and coatings on wires) substance. If no coatings are on the wires then $\varepsilon_{eff} = 1$.

For a half-wave TEM-line section $n = 1$ and $f_r = 375$ MHz. This value of f_r also provides the ability to receive averaged moisture data. However, if a substance with rather high water content is monitored then quality factor Q of such a resonator may be inadequate for registration of the informative parameter. There are a few methods to increase Q: covering both the conductors of such two-wire resonator with dielectric coatings; providing a gap between a monitored substance and the rollers; or both methods.

Several consequently connected rollers of the lattice isolated from the others may also be used for the synthesis of a TEM-line section. A conductor with zigzag form represents one of two conductors of the TEM-line; a nearby metal plate may serve as the other conductor. Both ends of this line section may be short-circuited. The resonance frequency of this resonator is thus decreased, and the depth of electromagnetic wave penetration into a moist substance and degree of moisture data averaging are appropriately increased.

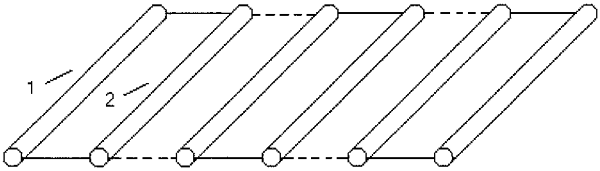

Fig. 8.3. Lattice made from metal rollers
1 and *2* – rollers as conductors of two-wire TEM transmission line

For contactless RF measurements several ways of placing a RF TEM transmission line-based sensor and a monitored material are possible. Figures 8.4a and 8.4b show the one-sided and two-sided contactless position of conductors 1 and 2 of two-wire RF-sensors relative to a monitored object 3. A monitored object is placed so that it provides effective influence on the electromagnetic field of such a sensor. As shown here, it is often valuable to cover conductors with dielectric coatings. It allows us to increase the quality factor of TEM line resonator sensors [1]. Various types of RF resonator sensors may be applied; their choice depends on the measuring problem to be solved.

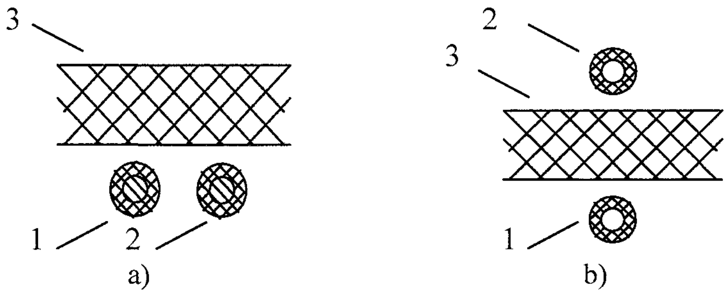

Fig. 8.4. One-sided (**a**) and two-sided (**b**) position of two-wire line conductors relative to a monitored object; *1* and *2* – conductors of two-wire transmission line, *3* – monitored object

Figure 8.5 presents one possible scheme for contactless on-line RF materials characterization. Here a two-wire RF transmission line section short-circuited at both ends is used as sensitive element. Characterized material 1 is placed within the area between the conductors of resonator 2. RF-oscillator 5 and measuring unit 6 (providing determination of resonance frequency f) are connected to resonator 1 via coaxial cables through coupling elements 3 and 4 that are inductive loops (in this simplified scheme we don't show matching elements for connecting coaxial cables with the two-wire line). Such a line section is half-wave resonator. The initial (without a material) resonant frequency f_0, used as the informative parameter, is expressed by Eq. (8.5).

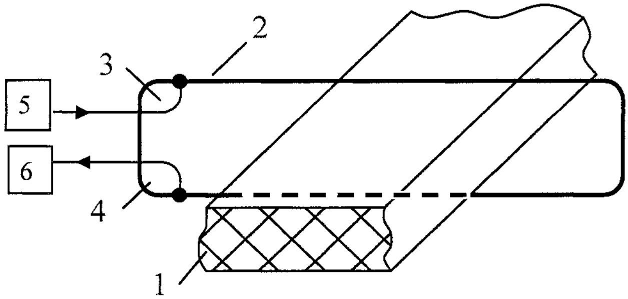

Fig. 8.5. RF-device containing two-wire resonator sensor
1 – monitored material, *2* – two-wire resonator, *3* and *4* – coupling elements,
5 – RF-oscillator, *6* – measuring unit

If a material is present between the conductors then for determination of the appropriate value of the resonance frequency f, the value of $\varepsilon_{eff\,0}$ in Eq. (8.5) should be replaced by ε_{eff}. Air is substituted by the real layered substance that is composed of wire coatings, a monitored material and air.

For example, if production of building materials (bricks) is considered and water content W in clay mass is determined [16] then we get the following data for a moist clay mass between the conductors of resonator 2. If f_0 = 300 MHz (l = 0.5 m), air gaps are 10 mm, then $f = 0.251 f_0$ = 75.3 MHz. If density of the dry substance (brick) is 1.2 g/cm^3 at temperature t = 20 – 60°C, brick dimensions are 24×12×6 cm^3 (clay volume is 1602.4 cm^3), produced bricks are porous, number of pores is 19, then for W = 25%, f/f_0 = 0.223, that is f = 67 MHz.

Figure 8.6 shows the calculated dependence of f/f_0 versus moisture W = 22 – 28 % (real values) at f_0 = 300 MHz. Here lines 1 and 2 are related to flows of continuous clay mass (without gaps between line conductors and this clay mass) and of porous clay mass (also without said gaps); line 3 is received for porous mass flow if gaps of 10 mm are present on both sides of this clay mass. From these data it follows the rather high sensitivity of the RF resonator moisture sensor.

For characterization of flowing materials in pipelines special TEM line-based resonator sensors are used [1, 18]. Their conductors are placed on the surface of the inner dielectric layer of a pipeline within the measuring section. No sensor parts are inside the pipeline. The electromagnetic field of such a resonator sensor with sufficient sensor sensitivity provides reliable determination of characterized material parameters. Distribution of the electromagnetic field intensity is uniform through the cross-section of the measuring section of a pipeline. It follows that various parameters (concentration of two-component substances, including in particular continuity of liquid-gas flows, etc.) of non-uniform flows can be measured with high accuracy. Measuring results are independent from distribution of flow components within the measuring section.

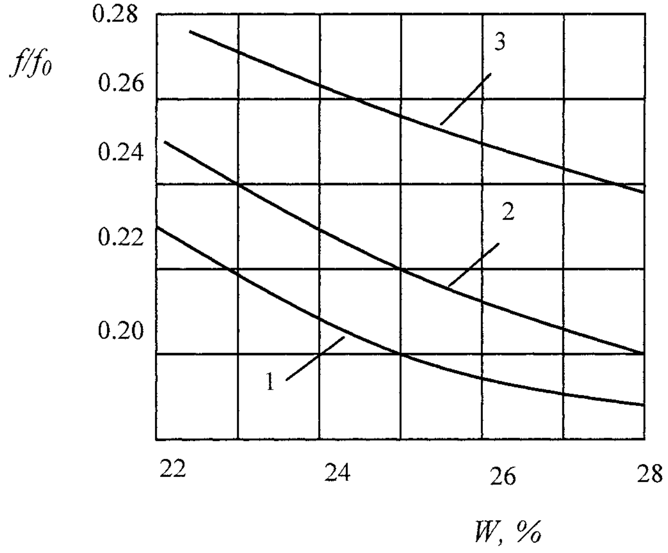

Fig. 8.6. Dependence of resonance frequency on clay moisture

8.2.2.3 Multiple-Probe Moisture Sensors for Measurements in Pipelines

Microwave moisture measurements in pipelines are often made using the sounding flow of a substance in the direction transverse to the flow [2, 3]. Transmitting and receiving antennas are connected to the pipeline. A drawback of such an approach is low measurement accuracy caused by a small layer of a monitored substance through which the microwave beam is propagated. In pipelines of large diameter (tens of centimeters), sounding of only a part of flow cross-section results in appropriate error. This is typical problem for flows of oil, oil products and chemicals. This error is significant especially for monitoring of non-uniform flows, in particular gas-liquid flows where distribution of gas inclusions is random. Use of the metal pipeline itself as a waveguide sensor [2, 5] doesn't allow for increased measurement accuracy because of non-uniform field distribution in the sensor's cross-section.

The use of microwave sensors with multiple probes can significantly increase measurement accuracy and sensitivity to measured variables, in particular to moisture of a substance. Simultaneous multiple probing of a flowing substance results in a significant increase of wave–substance interaction that is characterized by growth of phase shift, and power absorption of waves propagated through a substance.

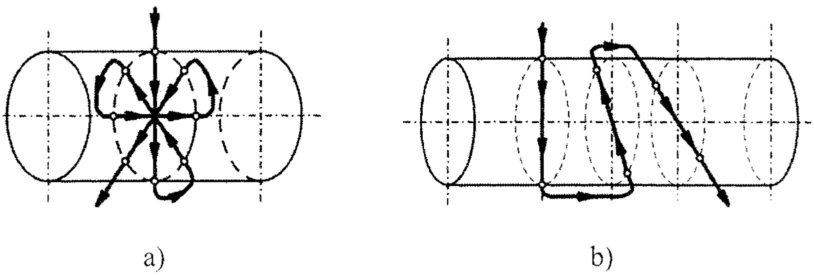

Fig. 8.7. Schemes of multiple soundings of a flowing substance in a pipeline through one (**a**) and various (**b**) cross-sections

A scheme of multiple soundings of a flowing substance in a pipeline through its cross-section plane using waves at different angles is shown in Fig. 8.7a. In particular such k soundings ($k = 2,3, \ldots$) may be at equal angles $360°/k$.

Multiple sounding of a flowing substance means increasing the path length by k-times for waves propagated through the monitored substance. Now path length is $d_k = kd$ (d is inner diameter of a pipeline, k is the number of soundings) in the cross-section of this pipeline. The value of a used informative parameter is also increased by k.

Significant decrease of non-monitored areas in the cross-section of a pipeline results in the averaging of moisture data. An advantage of this scheme in comparison with the single sounding scheme is that it gives measurements in narrow substance layer of the pipeline cross-section. The thickness of such a layer is determined by directivity diagrams of the antennas. In order to avoid interaction of electromagnetic waves under different angles (if it takes place), sounding of flow at different angles may be done in various sections along pipeline, transversely to flow direction in each such section (Fig. 8.7b).

A device with multiple soundings of a moist substance in a pipeline can be realized using k pairs ($k = 2,3, \ldots$) of transmitting antennas 2a, 2b, ..., 2k and corresponding receiving antennas 3a, 3b, ..., 3k that are connected to the pipeline. Each preceding antenna is connected to the next one by an appropriate waveguide. Excitation of waves is done by an oscillator. Waves received after multiple propagation through the cross-section of the pipeline are registered. It contains appropriate units depending on chosen informative parameter (amplitude, phase shift, etc.).

A sensitivity increase follows also from analytical consideration. If the informative parameter is the power or the amplitude of received waves then the loss factor N (in decibels) is

$$N = 8.686\alpha_w W\rho\gamma d + /R/ \tag{8.6}$$

where $/R/$ is module of reflection coefficient from interface "antenna-substance", d is the thickness of a substance layer, that is the inner diameter of a pipeline in this case, γ is the empirical constant taking into account structure of a substance, ρ is the density of the moist substance, α_w is the loss factor for water [7].

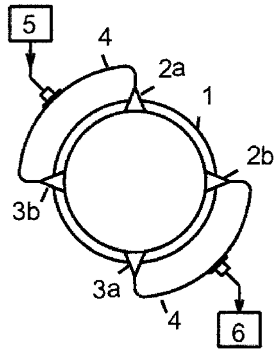

Fig. 8.8. Microwave device with multiple soundings of a moist substance in a pipeline (example)

It is seen that N is proportional to the thickness of the substance layer. Wave path length for $k = 2,3, \ldots$ soundings is kd; appropriately is increased the value of N.

Based on the above-described schemes, it is possible to design appropriate devices with resonator sensors. For this purpose the output of the last receiving antenna 3k is connected with input of antenna 2a. The resonator oscillations are excited in the cross-section of pipeline 1. Figure 8.8 shows an example of such a resonator moisture-measuring device. Antennas 2a, 2b and 3a, 3b here are transmitting-receiving. Pairs 2a, 3b and 3a, 2b are connected by waveguides 4 and are used for flow sounding in the direction transverse to the flow. Oscillator 5 and register 6, used to measure the resonance frequency of the synthesized resonator are also shown.

The natural (resonance) frequency f_n of electromagnetic oscillations of such a resonator can be expressed as:

$$f_n = \frac{n/k}{(d\sqrt{\varepsilon_m(W)})/c + l/v_{ph}} \tag{8.7}$$

ere $\varepsilon_m(W)$ is the dielectric permittivity of a substance with moisture W; l is the length of each waveguide 4 (it is admitted here equal for all the waveguides but this condition is not principal); v_{ph} is the phase velocity of waves in the waveguides 4; $n = 1.2,\ldots$; $k = 2.3,\ldots$. So, if $d = 0.3$ m; $l = 0.1$ m; $k = 2$ and $\varepsilon_m = 2$, then $f_n = 0.3n$ GHz (n is the number of the type of oscillations). It follows from Eq. (8.7) that the frequency change Δf_n of frequency f_n due to the change $\Delta\varepsilon_m$ (W) can be written as:

$$\Delta f_n(W) = \frac{f_n \Delta\varepsilon_m(W)}{2n^2 ck\varepsilon_m{}^{3/2}} \tag{8.8}$$

For instance it follows from this relationship that for $\Delta\varepsilon_m(W) = 1$, $n = 4$, $f_n = 1.2$ GHz we receive $\Delta f_n = 40$ MHz (~ 3.3 % of f_n); such a frequency change is practically enough for its registration. These data correspond in particular to the change of moisture in oil or oil products with $\varepsilon_m = 2$ within the range $W = 0 - 16.7$ %.

The considered approach is applicable for moisture measurements in pipelines of different diameters and those made from various materials (metal, dielectric, layered material, etc.). Areas of possible application may cover transportation of oil, oil products, chemicals, etc.

8.2.2.4 Split-Cavity Moisture Sensors for Sheet-Like Materials

The use of proposed split-cavity sensors provides both contactless monitoring of needed parameters of sheet-like materials and also independence of measurement results on a sheet (web) position within the split in a direction that is transverse to the direction of movement [17].

For this purpose uniform transverse distribution of electromagnetic energy must occur in this area (Fig. 8.9a). In the proposed resonator on the base of a rectangular waveguide 1, this approximately uniform distribution occurs (Fig. 8.9a shows the distribution of electric field amplitude E). Dielectric slabs 2 and 3 with thickness d and permittivity ε_s are placed on the opposite broad sides of the rectangular waveguide cross-section along its length. A TEM-mode field exists within the free central part of the resonator cross-section of this waveguide with initial mode H_{10} [19, 20].

The electromagnetic wave is transversal (TEM) if the following condition is met for the length λ of the electromagnetic wave for plane wave operation:

$$\lambda = 4d\sqrt{\varepsilon_s - 1} \qquad (8.9)$$

The nearly constant distribution of electromagnetic energy in the waveguide free space may be considered as the one present in the same substance within the split area.

Such an approach appeared effective in microwave heating applicators, which are used particularly in biology and medicine [21, 22]. Various dielectrics may be used as slabs: plexiglass ($\varepsilon_s = 2.59$), stycast ($\varepsilon_s = 7$), alumina ($\varepsilon_s = 10.07$), etc. So, for a waveguide with cross-section dimensions ≈ 7 by 3.5 cm and slabs with permittivity $\varepsilon_s = 7$ and thickness $d = 1.3$ cm, the needed operation conditions with TEM-field in the central area were provided at frequency 2450 MHz ($\lambda = 12.45$ cm) [21]. Uniform field distribution in this area is expected to be approximately the same if λ is not significantly changed due to a change of oscillator frequency or insertion of a dielectric object into the free space slightly perturbing the electric field.

A cavity resonator on the base of such a waveguide may serve as a sensor for measurements of some parameters, in particular those of moving sheet-like materials. Uniform energy distribution in such a waveguide 1 and in the resonator sensor based on it results in independence of measurement results on a sheet position in transverse direction in the central part.

Figure 8.9b shows a split-cavity sensor containing a moving dielectric material 4 within the split. Dielectric slabs 2 and 3 are in both parts of the cavity.

The resonator is supplied by cut-off waveguides formed by metal sheets 5 and 6 at the free edge on each half of the split-cavity.

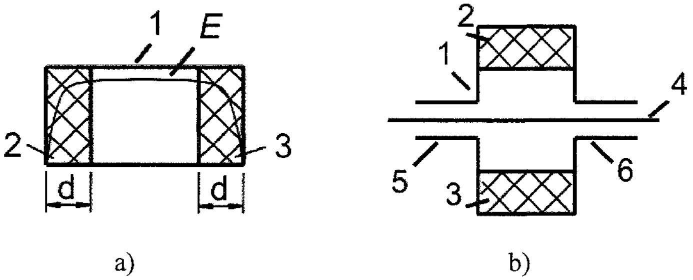

Fig. 8.9. Waveguide with TEM-mode field in its central part (**a**) and split-cavity sensor with a sheet within the split (**b**)
1 – waveguide, *2* and *3* – dielectric slabs, *4* - sheet-like material, *5* and *6* – metal sheets

Location of a sheet material within the split along the electric field component results in maximum sensor sensitivity. The same uniformity of energy distribution remains when the sheet thickness as well as its moisture W and density are changed, provided the sheet thickness a is small as compared with the resonator height l ($a << l$).

It can be shown that the dependence of resonance frequency f_r on sheet thickness a, permittivity ε_m is expressed as:

$$\frac{f_r}{f_{ro}} \approx 1 - \frac{a(\varepsilon_m(W) - 1)}{l} \tag{8.10}$$

here f_{r0} is initial value of f_r (in the absence of the sheet), l is length of the broad side of the split.

The value of ε_m depends on the density and the moisture of a material. Each of these parameters can be measured if sheet thickness a is constant. Measurements of a and/or W and also mass per unit area M may be done by measuring both resonance frequency f_r and amplitude A of the resonance pulse, or two (or more) resonant frequencies of various resonator modes, and by their subsequent functional transformation.

These measurements are needed in particular in pulp and paper industry. For example, a moving sheet may have width 4300 mm and have drift within ± 10 mm transverse to movement direction. When several resonator sensors are disposed across the monitored sheet profile of a, W and/or M distribution can be determined. This determination can be made simultaneously if more than one informational parameter is measured. In practice 10–20 split-cavity resonators can be installed in papermaking machines for manufacturing broad paper sheets (4300 mm). It may be done by measuring both resonance frequency f and amplitude A of resonance pulse and by their subsequent functional transformation. Thus current values of a, W and M may be found.

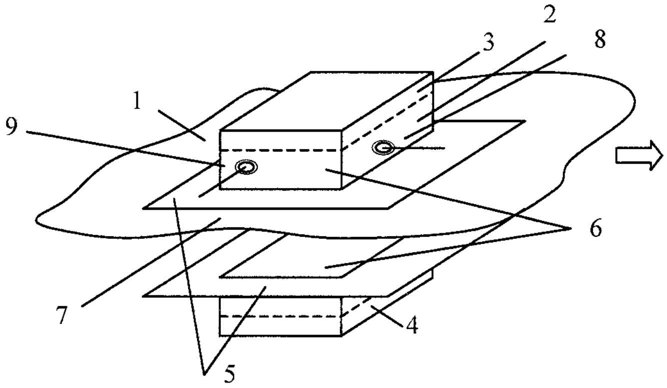

Fig. 8.10. Split-cavity sensor with a sheet within the split
1 – sheet-like material, *2* - resonator, *3* and *4* – dielectric slabs, *5* - metal sheet, *6* - open surface, *7* – split, *8* and *9* – coupling elements

Such an approach is also useful for invariant measurements when independence of measurement results of each of these parameters from other disturbing variables is required. Similar results are also obtained by measuring two (or more) resonant frequencies of various resonator modes. This approach is also applicable when independence of measurement results of each of these parameters from other disturbing variables is needed.

Figure 8.10 shows a split-cavity sensor containing a moving dielectric material 1 within the split of the resonator 2. Dielectric slabs 3 and 4 are contained in both parts of the split cavity. For on-line contactless measurements of moving sheet materials 1 this resonator is supplied by cut-off waveguides. They are formed by metal sheets 5 at the free edge on each half of the split-cavity resonator 2. Thus electromagnetic energy radiation from the cavity is prevented. Location of a monitored sheet material between open-ended surfaces 6 of the cavity 2 within the split 7 along the electric field line directions results in maximum sensitivity of the resonator-based sensor. The same energy distribution uniformity remains when sheet thickness, moisture and density are changed, if the measured sheet thickness a is small as compared with the resonator height l ($a << l$). Coupling elements 8 and 9 serve for excitation of electromagnetic oscillations in the cavity and its connection with an electronic unit measuring the value of the informative parameter (resonance frequency f).

8.2.2.5 Waveguide Resonator Moisture Sensors for Flowing Substances

A similar approach based on the use of dielectrically-loaded waveguides can be used for the design of resonator sensors for characterization of non-homogeneous dielectric substances in pipelines. In this case rectangular (Fig. 8.11a) or elliptical waveguide cavities can be synthesized. Waveguide 1 of resonator 5 contains dielectric slabs 3 and 4 at its broad walls and dielectric tube 2 with flowing material along its length. Thus independence of resonance frequency from distribution of inclusions (air bubbles, solid particles, etc.) in substances is provided. Tube 2 may have an exterior metal coating, which acts as cut-off waveguide relative to the waveguide cavity; sections of the metal pipelines 8 of the same diameter may also serve as such cut-off waveguides (Fig. 8.11b). Longitudinal twisting (90° or more as it is shown in Fig. 8.11c) of the resonator can be used for further accuracy improvement. This occurs due to spatial averaging of measurement results because of the angular change of the field pattern. Coupling elements 6 and 7 are used for connection of the sensor with the oscillator and electronic unit.

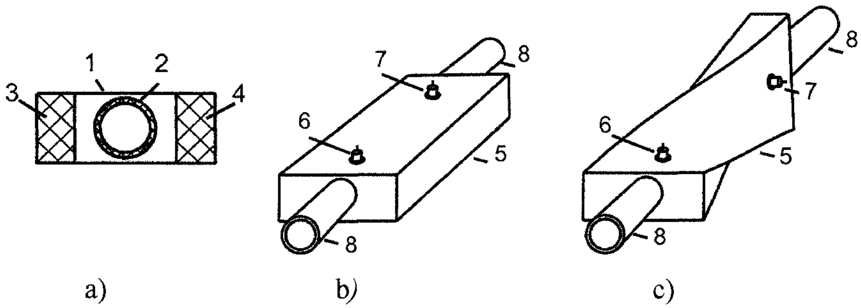

Fig. 8.11. Rectangular waveguide (cross-section) with dielectric slabs and tube (**a**); waveguide resonator sensor (**b**); twisted waveguide resonator sensor (**c**)
1 – waveguide, *2* – dielectric tube, *3* and *4* – dielectric slabs, *5* – waveguide resonator, *6* and *7* – coupling elements, *8* – pipeline section (cut-off waveguide)

8.3 Dielectric Permittivity/Density-Independent Resonator-Based Aquametry

During the determination of water content in various substances, the accuracy of measurement results may be significantly decreased by the influence of non-measurable parameters such as density, temperature, type, etc. Therefore it is very important to provide moisture measurements that are independent of the influence of non-measurables. Within microwave moisture measurement techniques some effective density-independent methods and means are known applicable for many actual areas [1–3, 10, 23–26].

Here we consider the microwave method that provides moisture measurement results independent of the dielectric permittivity of a monitored substance [27]. In turn this permittivity is functionally dependent on the type of a monitored substance or on various parameters (density, type, quality, etc.) of a certain substance.

Measurement Principles

This method is based on the fact that electrophysical parameters of water are frequency-dependent in the microwave frequency range. In particular, the dielectric permittivity ε_w of water is decreased with the increase of frequency f. Dependence $\varepsilon_w(f)$ is shown in Fig. 8.12. So, if $f = 16$ GHz then $\varepsilon_w = 42.5$; if $f = 37.5$ GHz, then $\varepsilon_w = 21.8$ (for the temperature 20°C). Therefore the permittivity ε of a moist substance is dependent on the value of ε_w for various microwave frequencies. Conversely, frequency dispersion absence is known for dielectric permittivity ε_s values of many solids and non-polar liquids (with the uncertainty of $2 \cdot 10^{-4}$) at the frequency range $10^{-2} - 10^{11}$ Hz [28].

This behavior of ε_w is the basis for water content W determination independently of the value of ε_s. In turn we assume the independence of non-measured parameters of a substance functionally connected with ε_s.

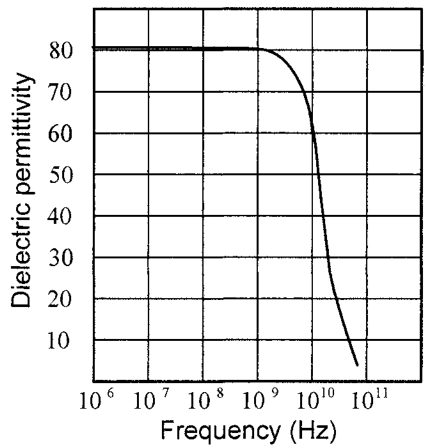

Fig. 8.12. Dielectric permittivity of water versus frequency

According to the proposed method, measurements of water content W are required at two frequencies f_1 and f_2. These frequencies are in ranges where ε_w has different corresponding values ε_{w1} and ε_{w2}. Values $\varepsilon_1(\varepsilon_s, \varepsilon_{w1}, W)$ and $\varepsilon_2(\varepsilon_s, \varepsilon_{w2}, W)$ of the permittivity of a moist substance are measured by a microwave measuring method (known or to be designed) according to certain measurement conditions. The frequencies f_1 and f_2 may be chosen in the following ways: 1) frequency f_1 is chosen on the part of the curve $\varepsilon_w(f)$ where the considered dispersion is absent, in particular within the frequency range less than 100 MHz; frequency f_2 is chosen on the dispersion curve part being in microwave range (Fig. 8.13a); 2) both frequencies f_1 and f_2 correspond to the dispersion part of the curve $\varepsilon_w(f)$ (Fig. 8.13b). For some substances, like non-polar dielectrics, ε_s is non-changeable at frequencies f_1 and f_2. Joint processing of $\varepsilon_1(\varepsilon_s, \varepsilon_{w1}, W)$ and $\varepsilon_2(\varepsilon_s, \varepsilon_{w2}, W)$ and allows for the determination of water content W independently of ε_s.

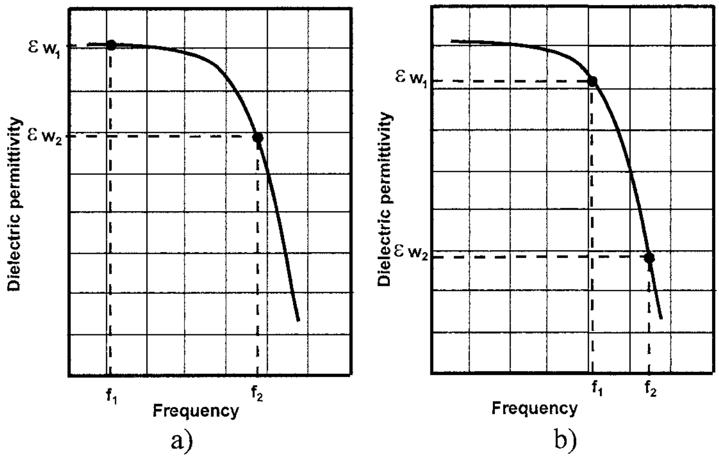

Fig. 8.13. Choice of two frequencies at the curve $\varepsilon_w(f)$

There is a need to know analytical dependence, $\varepsilon(\varepsilon_s, \varepsilon_w, W)$. If the dependence is not known for some substances it can be determined empirically and then with its approximation by an appropriate analytical expression.

Generally, the method is principally applicable for moist substances with various electrophysical parameters. Here application of the method is considered for some non-polar moist dielectrics, in particular water-in-oil emulsions. Their dielectric permittivity can be described analytically. As noted above, in the general case there is no requirement that the substance be a non-polar dielectric.

So, for some non-polar liquids (oil, oil products, etc.) at $W \leq 0.1$ it can be written [6]:

$$\varepsilon = \varepsilon_s \left(1 + \frac{3W}{D - W} \right) \tag{8.11}$$

where $D = \dfrac{\varepsilon_w + 2\varepsilon}{\varepsilon_w - \varepsilon_s}$.

Such an approach provides measurements of water content in a substance independently of ε_s. Taking into consideration expression Eq. (8.11), that is written for the frequencies f_1 and f_2, the system of these two equations is as follows:

$$\varepsilon(f_1) = \varepsilon_s \left(1 + \frac{3W}{D(f_1) - W}\right), \tag{8.12}$$

$$\varepsilon(f_2) = \varepsilon_s \left(1 + \frac{3W}{D(f_2) - W}\right) \tag{8.13}$$

here $D(f_1) = \dfrac{\varepsilon_w(f_1) + 2\varepsilon_s}{\varepsilon_w(f_1) - \varepsilon_s}$, $D(f_2) = \dfrac{\varepsilon_w(f_2) + 2\varepsilon_s}{\varepsilon_w(f_2) - \varepsilon_s}$.

The values $D(f_1)$ and $D(f_2)$ can be considered as constants for frequencies f_1 and f_2.

So, if measurements are undertaken at frequencies f_1 = 10 GHz and f_2 = 37.5 GHz, then corresponding values of D at $\varepsilon_s = 2$ are the following ones: $D(f_1) = 1.095$, $D(f_2) = 1.383$.

Equations (8.12) and (8.13) in the above system and its solution can be simplified under these conditions: 1) $D(f_1) - W \approx D(f_1)$, $D(f_2) - W \approx D(f_2)$; 2) these values don't depend on ε_s. These simplifications are permissible under small values of water content (up to $\cong$ 5%) and real relatively small limits of ε_s change.

Then after solution of the system of Eqs. (8.12) and (8.13) relative to W with exclusion of ε_s from the result, it can be found that:

$$W = \frac{1}{3} \frac{\varepsilon(f_1) - \varepsilon(f_2)}{\dfrac{\varepsilon(f_2)}{D(f_1)} - \dfrac{\varepsilon(f_1)}{D(f_2)}} \tag{8.14}$$

Various practical measurement methods are known providing determination of $\varepsilon(\varepsilon_s, \varepsilon_w, W)$ at two frequencies [1, 2]. Among them are methods for determination of phase shift, of reflection coefficient values, etc.

Values of $D(f_1)$ and $D(f_2)$ are constant at a fixed (measured) temperature for corresponding frequencies f_1 and f_2. It is so because the values of permittivities ε_s and ε_w are constant in formulae for $D(f_1)$ and $D(f_2)$. The value of ε_s is constant in a broad range of frequency f change. The value of ε_w is constant under changing f within the non-dispersive part of the curve $\varepsilon_w(f)$ and is considered constant on the dispersive part of this curve. This holds in the following cases:

– under measurements at fixed frequencies;
– under measurements of small values of water content using devices with changing frequencies, a situation often met in practice (in such cases f is changed non-significantly and, as a result the change of ε_w is very small and doesn't result in the error increase of water content determination over admittable value).

Change of temperature can be taken into account in Eqs. (8.12), (8.13) and (8.14), if the value of ε_w at a current (measured) temperature is used. Temperature change of ε_s doesn't significantly influence the values of $D(f_1)$ and $D(f_2)$.

It can be shown in practice that coefficients $3/[D(f_1) - W]$ and $3/[D(f_2) - W]$ at W in Eqs. (8.12) and (8.13) don't depend (with some admittable error) on ε_s. So, for a 10% change of ε_s compared with the initial value $\varepsilon_s = 2$, that is until the value

$\varepsilon_s = 2.2$, we obtain at $f_1 = 10$ GHz and $f_2 = 37.5$ GHz: $D(f_1) = 1.095$, $D(f_2) = 1.303$ for $\varepsilon_s = 2$; $D(f_1) = 1.105$, $D(f_2) = 1.337$ for $\varepsilon_s = 2.2$. It follows that the relative change of $D(f_1)$ is near 0.9%, and the relative change of $D(f_2)$ is near 2.6%.

It follows from these data that the relative change of both $3/[D(f_1) - W]$ and $3/[D(f_2) - W]$ is near 0.9% that is nearly ten times less than the relative change of ε_s. It means that real changes of ε_s don't practically influence on the above coefficients at W.

The considered method can also be realized using two resonator sensors (Fig. 8.14). Their informative parameters are resonant frequencies f_{r1} and f_{r2} that change depending on water content in a substance. Note that the dielectric permittivity of water $\varepsilon_w(f)$ is thus also changed on the dispersive part of this curve. Nevertheless such changes are known (because the current frequency of each resonator is known), as well as temperature-dependent change of ε_w (at a measured temperature). They can be taken into account in the computer unit of the resonator device.

For resonator measurements of water content independent of substance permittivity, the system of equations can be written:

$$\varepsilon_s\left(1+\frac{3W}{D(f_{r1})-W}\right)=\frac{f_{r1_0}{}^2}{f_{r1}{}^2}, \tag{8.15}$$

$$\varepsilon_s\left(1+\frac{3W}{D(f_{r2})-W}\right)=\frac{f_{r2_0}{}^2}{f_{r2}{}^2} \tag{8.16}$$

here f_{r1_0} and f_{r2_0} are initial (at $\varepsilon_s = 1$, $W = 0$) values of the resonant frequencies f_{r1} and f_{r2}, accordingly. Coefficients at W in Eqs. (8.15) and (8.16) for its small values are changed non-significantly with the change of frequency. Such changes in the general case are known and can be taken into account during computation of water content.

After solving this system of equations relative to W, we receive

$$W=\frac{1}{3}\,\frac{\dfrac{f_{r1_0}{}^2}{f_{r1}{}^2}-\dfrac{f_{r2_0}{}^2}{f_{r2}{}^2}}{\dfrac{1}{D(f_{r1})}\dfrac{f_{r2_0}{}^2}{f_{r2}{}^2}-\dfrac{1}{D(f_{r2})}\dfrac{f_{r1_0}{}^2}{f_{r1}{}^2}} \tag{8.17}$$

The value of W in Eq. (8.17) is independent of dielectric permittivity ε_s.

In the scheme for resonator measurements of water content in pipelines (Fig. 8.14) a monitored substance can flow through the basic pipe (shown) or through additional pipelines (bypasses).

Measuring resonators can be realized as constructions that allow free flowing through of monitored substances at both RF and microwave frequency ranges. Also they can have no parts inside the pipeline disturbing the flow. For example, such resonators can be open-ended with pipe parts at its both ends as cut-off waveguides; many other constructions can be used [2]. As it is shown in Fig. 8.14, resonators can be used as frequency-determining elements of corresponding self-excited oscillators. Output signals with frequencies f_1 and f_2 of these oscillators come to the computer unit for determination of water content independent of a substance permittivity.

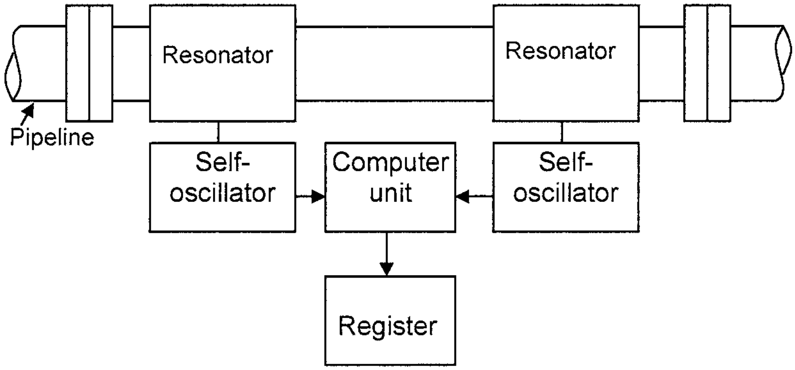

Fig. 8.14. Scheme for water content determination based on measurement of resonance frequencies of two resonators

8.4 Conclusion

The new design principles for RF and microwave resonator sensors of moisture/humidity considered here and the application of known RF/microwave resonator sensors in aquametry show that these techniques are applicable for highly accurate determination of water content in various liquid, solid, particulate, and gaseous substances. Many other technological parameters may also be effectively measured on the basis of such approaches.

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