Reentrant Resonators for Microwave Measurement Units

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Abstract **— The method of the calculation of the reentrant resonator based on the rectangular waveguide with inductive diaphragms or posts is demonstrated. The possibility of the applying such resonators as sensors for the uninterrupted technological processes is discussed in this paper. The sensors were designed and measured for two operating frequencies in L-band and X-band. The sensitivity of the sensors is sufficient to indicate the changing of the dielectric permeability and testing specimen diameter.**

I. Introduction

One of the main problems of the technology control automation is the receiving of the information about technology parameters and theirs changing during the process. The most attention is paid to the design of the effective measuring units and their basic elements-sensors. It is the common knowledge that the radio-frequency methods and means of the measuring including microwave frequencies have many functional possibilities. The transmission lines and resonators of various shapes commonly are used in such measuring systems as sensors; resonance frequencies of different modes, qualities, powers, amplitudes and phases in the guide systems are the informative parameters.

A sensitive element converting the information about the changing of the controlled parameters to the measured electrical quantities is one of the constituent parts of the technology parameter control units. In microwaves the cavity resonators are widely used as such sensitive elements, they transform changing of dielectric permeability or dimension of the controlled object to the measured parameters– a frequency shift, a quality change, a phase shift, etc.

It is well known that methods based on the measuring of the phase of reflected and transmitted signals ensure the maximal sensitivity. The cavity resonators with small electrical coupling can ensure very high quality (~50000) at the 1...10 GHz band. However in the some cases so high quantity of Q in the phase measuring isn't needed because it can lead to sharp changing in the phase characteristic of the resonance contour in the set frequency band. In this case it's reasonable to use reentrant resonator based on the resonance oscillations reflected from two inhomogeneities in the waveguide. Changing of the value of the inhomogeneity can regulate a quality and a transmission coefficient of these resonators in required limits.

II. Theory

The questions of the calculation of the reentrant resonators are considered in this section. The inductive diaphragms and inductive posts are used as inhomogeneities.

The equivalent admittance of the inductive diaphragm may be represent as [1]

$$y_1 = \frac{-i\Lambda_b}{atg^2 \dfrac{\pi d}{2a}}, \tag{1}$$

where a – a width of a waveguide, d– a width of a diaphragm, $\Lambda_b = \lambda_0 \Big/ \sqrt{1-\left(\dfrac{\lambda}{2a}\right)^2}$.

The scattering matrix of the reentrant resonator with two identical inductive diaphragms can be represented as

$$S_{11} = -\frac{y}{2+y}e^{-\beta l},\ S_{22} = S_{11}, S_{21} = S_{12} = \frac{2}{2+y}e^{-\beta l}, \tag{2}$$

where

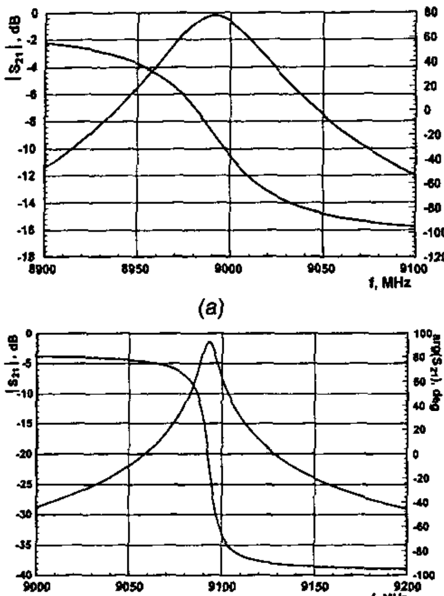
$$y = \frac{2y_1}{ch^2\dfrac{\beta l}{2} - y_1 sh^2\dfrac{\beta l}{2}}, \qquad \beta = \alpha + i\gamma, \tag{3}$$

$$\alpha = \frac{1+\dfrac{2b}{a}\left(\dfrac{\lambda}{2a}\right)^2}{b\sqrt{1-\left(\dfrac{\lambda}{2a}\right)^2}\sqrt{120\sigma\lambda}}, \qquad \gamma = \frac{2\pi}{\Lambda_b}$$

The loss power and input VSWR of the resonator are denoted by elements of the scattering matrix

$$P_L = 1-|S_{11}|^2-|S_{21}|^2, \qquad K_{cmV} = \frac{1+|S_{11}|}{1-|S_{11}|} \tag{4}$$

Changing diaphragm width d may change the quality, the phase characteristic and the transmission coefficient of the resonator. The modulus and phase of the transmission coefficient for two values of d (d= 5 mm, d= 8 mm) are shown at the Fig 1.



(a)

(b)

Fig.1. The modulus and phase of the transmission coefficient: (a) inductive post diameter d= 5 mm; (b) inductive post diameter d= 8 mm

The equivalent scheme of the inductive post of the diameter d can be represented as T-shaped couple of three reactive resistors with values calculated at [1]:

$$x_b = \frac{a}{\Lambda_b}\frac{\left(\frac{\pi d}{a}\right)^2}{1+\frac{1}{2}\left(\frac{\pi d}{\lambda}\right)^2\left(R_2+3/4\right)};$$

$$x_a = \frac{a}{2a_b}\left(R_0-\left(\frac{\pi d}{2\lambda}\right)^2-5/8\left(\frac{\pi d}{2\lambda}\right)^4-2\left(\frac{\pi d}{2\lambda}\right)^4\left(R_2-2R_0\frac{\lambda^2}{\Lambda_b{}^2}\right)^2\right)+x_b/2$$

$$R_0 = \ln\frac{4a}{\pi d}-2+2\sum_{n=3,5}^{\infty}\left(\frac{1}{\sqrt{n^2-\left(\frac{2a}{\lambda}\right)^2}}-\frac{1}{n}\right) \quad (5)$$

$$R_2 = \ln\frac{4a}{\pi d}-\frac{5}{2}+\frac{11}{3}\left(\frac{\lambda}{2a}\right)^2-\frac{\lambda^2}{2}\sum_{n=3,5}^{\infty}\left(\sqrt{n^2-\left(\frac{2a}{\lambda}\right)^2}-n+\frac{2}{n}\left(\frac{\varepsilon}{\lambda}\right)^2\right)$$

After simple transformations the equation for the scattering matrix of two equivalent posts can be obtained:

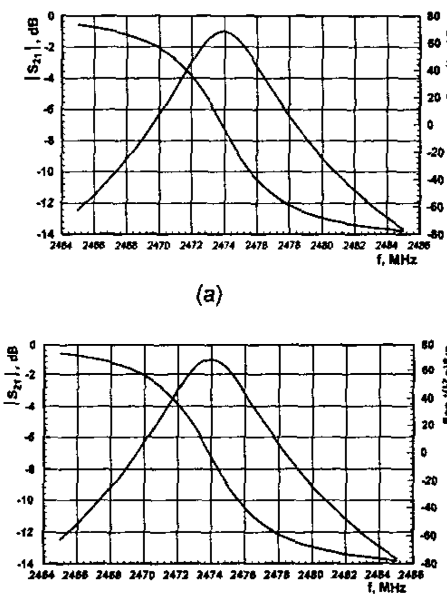
$$S_{11} = S_{22} = \frac{1}{\Delta}\left(s-\frac{4x_a^2 s e^{-2\beta l}}{\Delta^2-s^2e^{-2\beta l}}\right) \quad (6)$$

$$S_{21} = S_{12} = -\frac{4x_a^2 e^{-2\beta l}}{\Delta^2-s^2e^{-2\beta l}}$$

where $s = 2x_b\left(x_a-\frac{x_b}{2}\right)-1,\ \Delta = (1+i(x_a-x_b))^2+x_a^2\cdot$

Changing the post diameter can change the resonator parameters; the modulus and phase of the transmission coefficient for two values of d (d=10 mm, d=20 mm) are shown at Fig. 2.

The analysis of represented data permits to make a conclusion that both constructions of resonators are fit as the base of the microwave sensors, the choice of construction is determined by requirements of the simplicity and the technology of the production of these control units.



(a)

(b)

Fig.2. The modulus and phase of the transmission coefficient: (a) inductive post diameter d= 10 mm; (b) inductive post diameter d= 20 mm

III. Experimental Results

Our sensors are destined for the applying in the parameter control devices used in the manufactory of the dielectric cord -shaped products. It is known that the frequency shift in the rectangular resonator for the cord passing in the narrow wall parallel direction can be represent as:

$$\frac{\delta f}{f_0}=\frac{2(\varepsilon_r-1)Ab}{V_0}, \tag{7}$$

and for the cord passing in the narrow wall perpendicular direction in the same resonator [2]:

$$\frac{\delta f}{f_0}=\frac{2(\varepsilon_r-1)Aa}{(\varepsilon_r+1)V_0}, \tag{8}$$

where f_0 – a resonance frequency of an unfilled resonator, V_0– a volume of a resonator, ε_r – a dielectric permeability of the cord material, A– a cross-section square of the cord ($A=\frac{\pi d^2}{4}$).

Equations (7), (8) form the linear system regarding dielectric permeability ε_r and cross-section square of the cord A. The solution of this system can be represented as:

$$\varepsilon_r=\frac{a}{b}\frac{\Delta_\parallel}{\Delta_\perp}-1,\ A=\frac{V_0\Delta_\parallel}{2a\left(\frac{\Delta_\parallel}{\Delta_\perp}-2\frac{b}{a}\right)}, \tag{9}$$
$$\Delta_\parallel=\left(\frac{\delta f}{f_0}\right)_\parallel,\ \Delta_\perp=\left(\frac{\delta f}{f_0}\right)_\perp.$$

In the realization of the control unit two consecutive resonators or rectangular resonator with orthogonal exiting can be used. During the continuous integrity control of the dielectric cords it is expediently to use reduced height clearance for the achievement the highest resolution of the diameter control method. The possibility of the sensor production for two frequency bands 2.45, 9 GHz was considered, the advantage of the former is the ISM permitted frequency band, the advantage of the latter is the possibility of the sensor miniaturization. The construction of the sensor consists of a section of the rectangular waveguide with coaxial-waveguide transitions where the reentrant resonator is formed by two identical inhomogeneities such as inductive diaphragms and inductive posts. The controlled cord passes through the maximum of the electric field parallel of the electric field intensity across the opening in the wide wall of the waveguide. The sensitivity of the sensor to the changing of the dielectric permeability and cord's diameter can be obtained by the derivation the equation (7).

$$\frac{\partial(\delta f)}{\partial\varepsilon_r}=\frac{\pi f_0}{2al}\frac{b_0}{b}d^2,\quad \frac{\partial(\delta f)}{\partial d}=\frac{\pi f_0}{al}\frac{b_0}{b}d(\varepsilon_r-1), \tag{10}$$

where a, b, l – a width, a height, a length of a resonator, d – a diameter of a cord, b_0– a height of a cord section in the resonator.

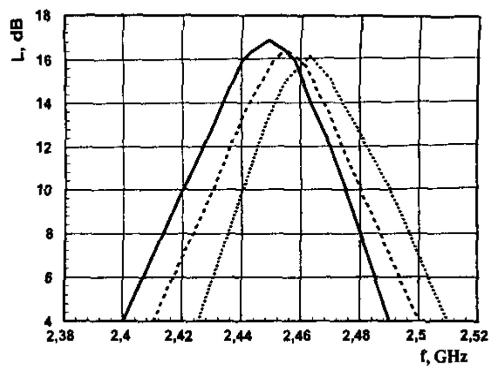
For the cord with diameter equal to 6 mm and $\varepsilon_r\approx 2$ the following sensitivity estimations were obtained: in the L- band $\frac{\partial(\delta f)}{\partial\varepsilon_r}\approx 0.17$ MHz/%, $\frac{\partial(\delta f)}{\partial d}\approx 5.8$ MHz/mm, in the X- band $\frac{\partial(\delta f)}{\partial\varepsilon_r}\approx 32$ MHz/%, $\frac{\partial(\delta f)}{\partial d}\approx 107$ MHz/mm. So, the potential sensitivity of this method is quietly enough for the product parameter testing with the 5...10% accuracy.

Two model based on 72x10 mm^2 and 23x10 mm^2 waveguides were made, in the former model the reentrant resonator with inductive posts of 140 mm length with H_{101} mode and resonance frequency 2.45 GHz was used, in the latter the inductive diaphragms were used, the length of resonator is equal 70 mm, H_{103} mode with resonance frequency 9.15 GHz is exited. Two models of the firing cords with diameter d=6 mm and filling explosive material TEN ($C(CH_2ONO_2)_4$) with $\varepsilon_r=1{,}5...2{,}5$ produced by Russian plant "Iskra" were used as controlled samples.

The first model of firing cords is fabricated by the extruding technique. During this process the explosive component may be replaced by the shelling dielectric material with different permeability. This reduced the explosive characteristic.

In the second model of firing cords the explosive material is coated by cotton threads and the diameter control is necessary to prevent explosive gaps.

The measurements were realized with the VSWR and attenuation-measuring units P2-53 and P2-104 by the attenuation-measuring scheme. At the L- band frequency shift after resonator filling is equal 15 MHz, the measured quantity of Q is 90. At the X- band frequency shift exceeds 120 MHz, the measured quantity of Q is more 500. The experimental results are shown at Fig. 3.



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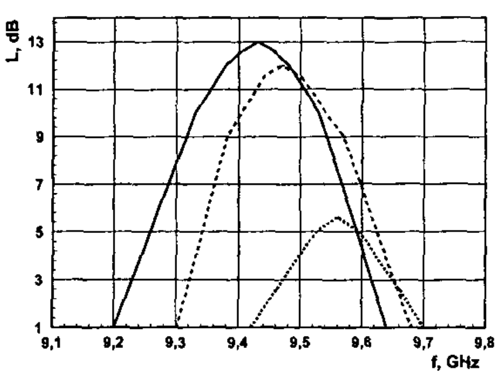

(b)

Fig.3. The measuring results: (a) inductive post diameter d= 10 mm; resonance frequency 2,5 GHz; (b) inductive diaphragm; resonance frequency 9,43 GHz:
solid lines –an empty resonator; dashed lines- a defective cord testing; dotted lines - a qualitative cord testing

In the both cases the visual detected defects of the product were indicated with confidence. Evidently at the control systems design the X - band is preferable because of its higher sensitivity and miniaturization of a sensor.

IV. Conclusion

The results of the reentrant resonator design based on the resonance oscillation reflected from two inhomogeneities placed in the rectangular waveguide has presented. This kind of excitation is simple and effective so reentrant resonators can be used as microwave sensors for various technological processes such as diameter testing of specimen with different dielectric permeability. The basic characteristics for two frequency bands had calculated and the measured results were described.

References

[1] N. Marcuvitz, *Waveguide Handbook*, New York: McGraw-Hill, 1951.

[2] V.A.Viktorov, B.V. Lunkin, A.S. Sovlukov, *Microwave Measuring of Technological Process Parameters*, Moscow: Energoatomizdat, 1989 (in Russian)