The Power Parameters of Semi-Opened Waveguide Junctions with Dielectric

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***Abstract*- This work is the continuation of series of works on research of physics of resonant phenomena in waveguide junctions of various cross-section and to their using for measurement of electric characteristics of materials. The comparative characteristic of eigen *Q*-factor waveguide junctions of various cross-section section has been given: cylindrical - radial waveguides, rectangular - rectangular waveguides, cylindrical – rectangular waveguides. The recommendations on using of concrete type of waveguide junctions for measurement of dielectric losses of the certain materials has been given.**

Keywords*- *Waveguide Junctions; Permittivity; Dielectric Losses

I. INTRODUCTION

To the electromagnetic oscillations in the X- and T- waveguide junctions a great number of works are devoted [1-5]. The free two-dimensional oscillations [1] and three-dimensional oscillations [2] in the junctions of rectangular waveguides, axisymmetric [3] and asymmetrical [4] oscillations in the junctions of cylindrical waveguides were investigated. The spectrums of quasi-eigen oscillations in such structures were investigated [4, 5]. It is explained by their use in a microwave technique: as component parts of passive and active devices [6], as measurement devices for determination of electric parameters of dielectrics without their destruction [7]. The knowledge of dielectric losses in materials plays an important role both for metrological certification of materials, and for radio engineering devices into which structure they enter as presence of dielectric losses renders essential influence on their work. The topic of characterizing the losses in a resonator is very important for microwave engineering, specially for filter designers [8]. Moreover, sometimes it is important to know dielectric loss tangent ($\mathrm{tg}\delta$) not in all volume of the sample (integrated losses), and in its concrete part (so-called local losses): for example, in that part which is in the center of the resonator and renders the most essential influence on work of the device. Frequently it is necessary to receive such information without destruction of the sample from an investigated material owing to its high cost or labour input of its manufacturing.

Scantily explored is a question about *Q*-factor of the waveguide junctions of complicated configurations. The aim of this work is to present a strong electrodynamic calculation of power parameters of waveguide junctions of different configurations and their comparative analysis. It is necessary for recommendations on using of concrete type of waveguide junctions for measurement of dielectric losses of the certain materials.

II. THE ELECTRODYNAMIC AND NUMERICAL ANALYSIS

A. *The Junction of Cylindrical-Radial Waveguides*

The investigated structure is shown in Fig. 1. Region II - is a cylindrical waveguide of radius *a*; region III (IV) - a radial waveguide of radius *b*; I - is a region of junction (coupling) of waveguides. Each of regions was filled by dielectric with permittivity $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$ ($\varepsilon_3 = \varepsilon_4$) accordingly ($\varepsilon = \varepsilon^{/} - i\varepsilon^{//}$, $i = \sqrt{-1}$). In works [9] the electrodynamic problem of H_{0mn} - modes resonant frequencies calculation (*o, m, n* - are the number of field semi-variations on coordinates φ, *r, z*) was solved. In the given work the expression for eigen Q_0 - factor, which on known resonant frequencies allows to determine a local losses of electromagnetic energy in that part of the sample which is in the field of coupling of waveguides have been received. It is possible because all waveguides (II and III, IV) are cut-off on resonant frequency, except for region I. An eigen Q_0 - factor is determined by expression (1):

$$\mathrm{Q}_0 = \frac{k_0 \cdot W_{\mathrm{Res}}}{P_\partial + P_\sigma}, \tag{1}$$

where W_{Res} - the electromagnetic energy reserved in each four regions of the resonator; P_{∂} - the dielectric losses; P_{σ} - the losses in metal walls of waveguides; $k_0 = \frac{2\pi}{\lambda}$ (λ - the resonant wavelength of electromagnetic mode).

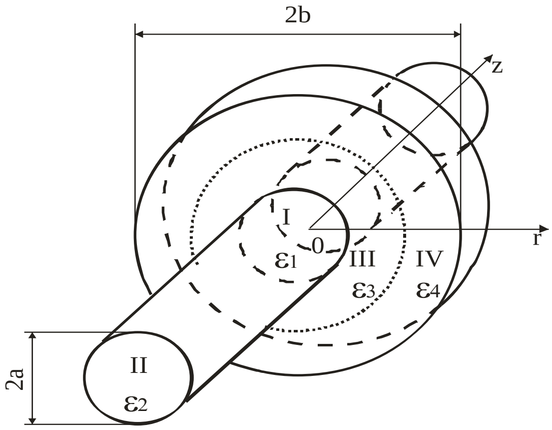

Fig. 1 Junction of cylindrical-radial waveguides

Omitting intermediate calculations, we shall write out final expressions for W_{Res}, P_{∂}, P_{σ} (2)-(4):

$$W_{\mathrm{Res}} = \frac{\pi \cdot a^2}{4} \sum_n A_{0n}^2 \left\{ \frac{2 \cdot \varepsilon_2^{/}}{\gamma_{an}^{II}} + \varepsilon_1^{/} \frac{l + \frac{1}{\gamma_{an}^{I}} \sin\left(\gamma_{an}^{I} l\right)}{\cos^2\left(\gamma_{an}^{I} l/2\right)} + \right. ,$$
$$\left. + \sum_g \frac{16 \cdot p_{1n}^2 \cdot p_{2g}^2}{l \cdot \left[p_{2g}^2 - \gamma_{an}^{I\,2}\right]^2 \cdot F_g^2} \left[\varepsilon_1^{/} - \varepsilon_1^{/} \cdot f_g^{I} + \varepsilon_3^{/} - \varepsilon_3^{/} \cdot f_g^{III} + \frac{4 \cdot F_g \cdot \varepsilon_1^{/}}{\left(p_{1n}^2 + \gamma_{eg}^2\right) \cdot a} \right] \right\}, \tag{2}$$

$$P_{\sigma} = \frac{\pi \cdot a^2}{4} R_s \sum_{n,g} A_{0n}^2 \left[\frac{4 \cdot p_{1n}^2}{\mathrm{k}_0^2 \cdot a \cdot \gamma_{an}^{III}} + \frac{16 \cdot p_{1n}^2 \cdot p_{2g}^4}{k_0^2 \cdot l^2 \cdot F_g^2 \left(p_{2g}^2 - \gamma_{an}^{I\,2}\right)^2} \left(f_g^{III} - 1\right) \right], \tag{3}$$

$$P_{\partial} = \frac{\pi \cdot a^2}{4} \sum_{n,g} A_{0n}^2 \left\{ \frac{k_0 \cdot \varepsilon_1^{//} [l + \sin(\gamma_{an}^{I} \cdot l)/\gamma_{an}^{I}}{\cos^2(\gamma_{an}^{I} \cdot l/2)} + \frac{8 \cdot p_{1n}^2 \cdot p_{2g}^2 \cdot k_0}{l \cdot F_g^2 (p_{2g}^2 - \gamma_{an}^{I})^2} [\varepsilon_1^{//} - \varepsilon_1^{//} \cdot f_g^{I} + \varepsilon_3^{//} \cdot f_g^{III}] + \right.$$
$$\left. + \frac{64 \cdot \varepsilon_1^{//} \cdot p_{1n}^2 \cdot p_{2g}^2 \cdot k_0}{l \cdot a \cdot F_g \cdot (p_{1n}^2 + \gamma_{an}^{I\,2}) \cdot (p_{2g}^2 - \gamma_{an}^{I})^2} \right. \tag{4}$$

where A_{0n} are amplitude of waves in cylindrical waveguide. Expressions for constants of propagation (attenuation) look like: $\gamma_{an}^{I} = [p_{1\mathrm{n}}^2 - k_0^2 \varepsilon_1^{/}]^{1/2}$, $\gamma_{lm}^{I} = [\frac{m \cdot \pi}{l} - k_0^2 \varepsilon_1^{/}]^{1/2}$, $\gamma_{an}^{II} = [p_{1\mathrm{n}}^2 - k_0^2 \varepsilon_2^{/}]^{1/2}$, $\gamma_{lm}^{III} = [(\frac{m \cdot \pi}{l})^2 - k_0^2 \varepsilon_3^{/}]^{1/2}$; $\gamma_{gm}^{III} = [(\frac{g \cdot \pi}{l})^2 - k_0^2 \varepsilon_3^{/}]^{1/2}$ R_{s} - losses in walls of waveguides (superficial resistance); l - is a transversal size of radial waveguide; $f_g^{I} = \frac{I_0(\gamma_{lg}^{I} a) \cdot I_2(\gamma_{lg}^{I} a)}{I_1^2(\gamma_{lg}^{I} a)}$; $f_g^{III} = \frac{K_0(\gamma_{lg}^{III} a) \cdot K_2(\gamma_{lg}^{III} a)}{K_1^2(\gamma_{lg}^{III} a)}$; $F_g = \frac{\gamma_{lg}^{I} \cdot I_0(\gamma_{lg}^{I} a)}{I_1(\gamma_{lg}^{I} a)} + \frac{\gamma_{lg}^{III} \cdot K_0(\gamma_{lg}^{III} a)}{K_2(\gamma_{lg}^{III} a)}$;

$I_0(\gamma_{lg}^{I}a)$, $I_1(\gamma_{lg}^{I}a)$, $I_2(\gamma_{lg}^{I}a)$, $K_0(\gamma_{lg}^{III}a)$, $K_1(\gamma_{lg}^{III}a)$, $K_2(\gamma_{lg}^{III}a)$ - are the modified Bessel functions of first kind and McDonald's functions of zero, first and second orders accordingly; $p=\frac{g\cdot\pi}{l}$, $p_{1n}=\frac{\nu_{0n}}{a}$, ν_{0n} - roots of equation $J_1(\nu_{on})=0$ (where J_1 - Bessel function of the first kind of the first order), *m, n, g* = 1,2,3 …

The dependencies of eigen Q_0- factor of H_{011} - mode of waveguide junction with cylindrical disk in the coupling region on dielectric losses factor for of some values of waveguides walls superficial resistance were resulted in Fig.2. From diagrams it is visible that Q_0 at absence of losses in dielectric and $R_s=R_{sm}$ (R_{sm}- superficial resistance of copper) spire to value Q_0=11950. Therefore, in such resonator it is possible to measure the factor of dielectric losses up to value $\mathrm{tg}\delta\approx 8\cdot 10^{-5}$.

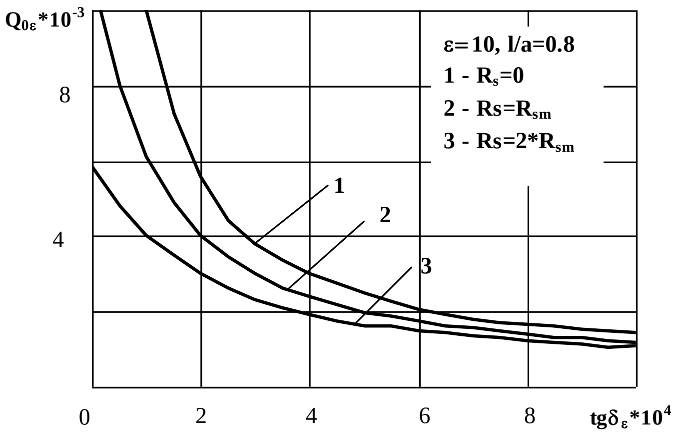

Fig. 2 Q_0 -factor value dependence of H_{011} -mode of cylindrical-radial waveguides junction with a disk on superficial resistance value R_s

B. The Junction of Rectangular - Rectangular Waveguides

The investigated structure is shown in Fig. 3. In works [10] the electrodynamic problem of H_{mn0} - modes resonant frequencies calculation was (m, n, o - are the number of field semi-variations on coordinates *x, y, z*). We shall result only final expression for eigen Q_0^H -factor of H_{mn0} - mode and results of numerical calculation:

$$Q_0^H=k_0\frac{W_{\text{Res}}^{(1)}+W_{\text{Res}}^{(2)}+W_{\text{Res}}^{(3)}}{k_0\cdot tg\delta\cdot W_{\text{Res}}^{(1)}+P_\sigma^{II}+P_\sigma^{III}}, \tag{5}$$

where $W_{\text{Res}}^{(i)}$ - the electromagnetic energy reserved in corresponding regions of the resonator; P_σ - the losses in metal walls of waveguides; $tg\delta=\varepsilon_1^{//}/\varepsilon_1^{/}$.

$$\mathrm{W}_{\text{Res}}^{(1)}=A_n^2\{\frac{b\cdot d\cdot\varepsilon_1^{/}}{4\cdot H_n}[\gamma_{nb}^{I}\cdot a+\sin(\gamma_{nb}^{I}\cdot a)]+\frac{a\cdot d\cdot\varepsilon_1^{/}}{4\cdot H_n}[\gamma_{nb}^{I}\cdot a+\sin(\gamma_{ma}^{I}\cdot b)]\}, \tag{6}$$

$$W_{\text{Res}}^{(2)}=A_n^2\frac{b\cdot d}{4\cdot\gamma_n^{II}},\ W_{\text{Res}}^{(3)}=A_n^2\frac{a\cdot d\cdot S_m^{+}}{8\cdot P_m},\ P_\sigma^{II}=A_n^2\frac{R_s}{k_0^2}[\frac{\pi^2}{2\cdot b\cdot\gamma_n^{II}}+\frac{\pi^2}{b^2\cdot\gamma_n^{II}}+\frac{\gamma_n^{II}\cdot b}{2}]; \tag{7}$$

$$P_m=\gamma_m^{III}sh^2\left(\gamma_m^{III}\frac{c-b}{2}\right);\quad S_m^{+}=sh\left(\gamma_m^{III}\left(c-b\right)\right)+\gamma_m^{III}\left(c-b\right);\ H_n=\gamma_{nb}^{I}\cdot\cos^2\left(\gamma_{nb}^{I}\cdot\frac{a}{2}\right); \tag{8}$$

$$P_{\sigma}^{III} = \frac{R_s}{4 \cdot k_0^2 \cdot P_m} \{[\gamma_m^{III^3} \cdot a \cdot (c-b) - a \cdot \gamma_m^{III^2} \cdot \sin(\gamma_m^{III}(c-b))] + \\ + \frac{\pi^2}{a}(\gamma_m^{III}(c-b) - \sin(\gamma_m^{III}(c-b)) \cdot (1 + \frac{2d}{a})) + 2 \cdot \gamma_m^{III^3} \cdot a \cdot d\}. \tag{9}$$

Expressions for propagation (attenuation) constants look like:

$$\gamma_{nb}^{I} = \left[\left(\frac{n\pi}{b}\right)^2 - k_o^2 \varepsilon_1'\right]^{1/2}; \gamma_{ma}^{I} = \left[\left(\frac{m\pi}{a}\right)^2 - k_o^2 \varepsilon_1'\right]^{1/2}; \ \gamma_n^{II} = \left[\left(\frac{n\pi}{b}\right)^2 - k_o^2\right]^{1/2}; \gamma_m^{III} = \left[\left(\frac{m\pi}{a}\right)^2 - k_o^2\right]^{1/2}; \ m, \ n = 1,2,3\ldots$$

$\varepsilon_1^{/}$ - dielectric permittivity (a dielectric fills the area I only); parameters *a, b, c, d* are indicated on Fig. 3.

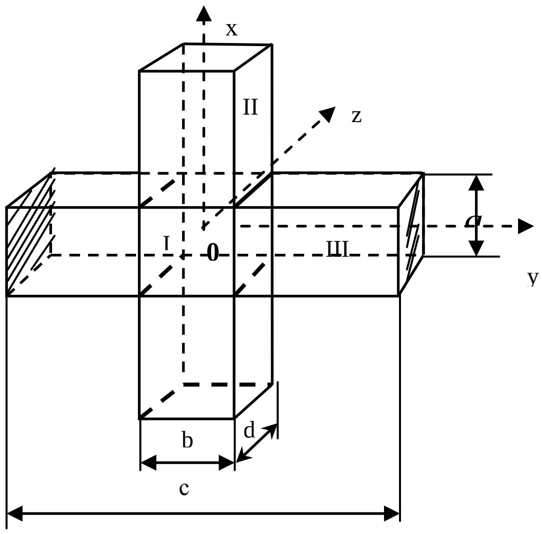

Fig. 3. Junction on rectangular waveguides

On Figs. 4-5 dependencies of eigen Q_0 -factor value of H_{110} -mode on value of dielectric loss tangent $\lg(tg\delta)$ and superficial resistance of waveguides walls R_s were resulted.

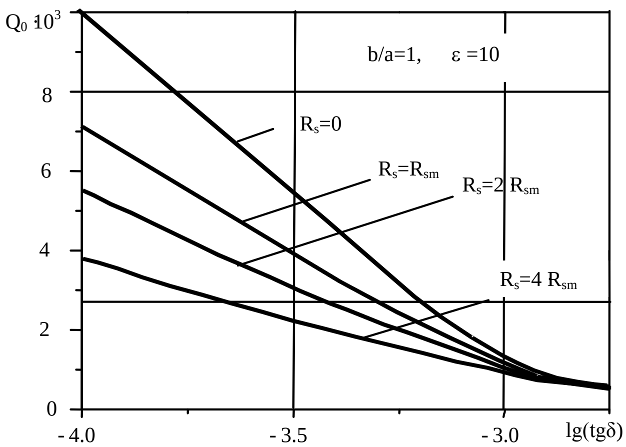

Fig. 4 Dependence of eigen Q_0 -factor value of H_{110} -mode on loss tangent for various values R_s (R_{sm}- superficial resistance of copper)

From diagrams it is visible that at $\mathrm{tg}\delta = 1\cdot 10^{-3}$ ($\lg tg\delta \le -3$) the basic influence on Q_0 is rendered with losses in walls of waveguides. The maximal numerical value of eigen Q_0 - factor at $\mathrm{tg}\delta = 1\cdot 10^{-4}$ and $R_s = 0$ for H_{011} mode was made $Q_0 = 10080$.

C. The Comparative Characteristic of Eigen Q-Factor of Semi-Opened Waveguide Junctions Loaded with Dielectric with Losses

In Fig. 6 dependences of eigen Q_0-factor of electromagnetic modes of H - type (as the highest quality) on dielectric loss tangent for various types of junctions were resulted: cylindrical - radial waveguides (curves 1, 2); cylindrical - rectangular waveguides (3, 4) [11]; rectangular - rectangular waveguides (5,6). From diagrams it is visible that the junction of the highest quality is the first type of junction. Therefore, in such structures it is possible to measure dielectric losses in samples both cylindrical, and plane, made of high-quality materials. In the devices made of copper, or covered by precious metals (silver, etc.), the measurement of dielectrics with losses up to $\mathrm{tg}\delta = 8\cdot 10^{-5}$ is possible. In junctions of cylindrical-rectangular waveguides it is possible to measure samples both cylindrical, and the rectangular form of cross-section with factor of dielectric losses up to $\mathrm{tg}\delta = 1\cdot 10^{-4}$. Junctions on the basis of rectangular waveguides are intended for measurement of rectangular parallelepipeds with factor of dielectric losses up to.

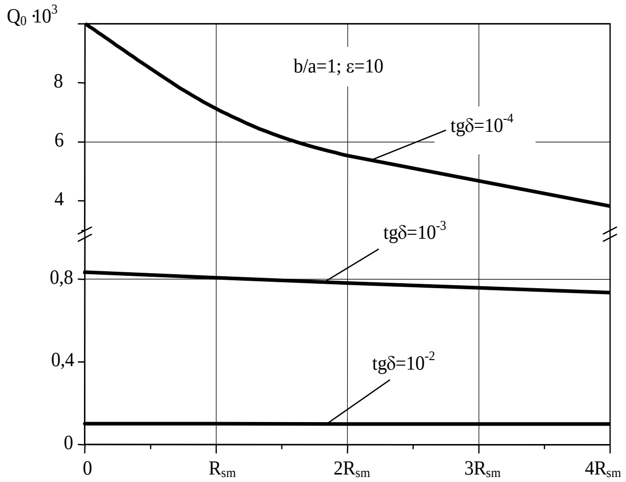

Fig. 5 Dependence of size of eigen Q_0 -factor value of H_{110} -mode on superficial resistance value $\mathbf{R_s}$

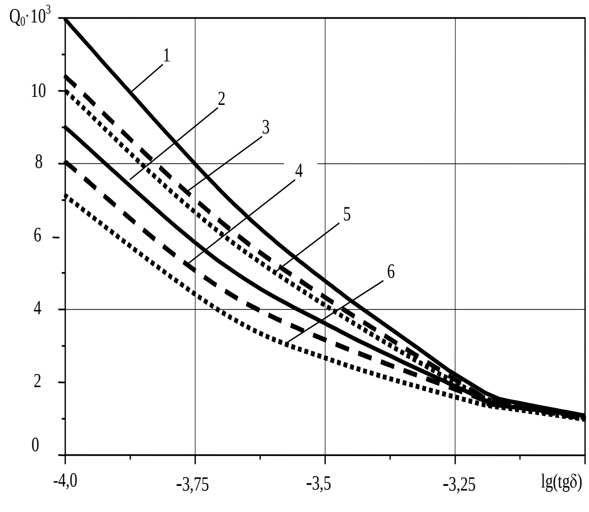

Fig. 6 Dependence of eigen Q_0-factor value on loss tangent tgδ for various types of junctions, loaded with dielectric: ε=10; b/a=1; curves 1 and 2 - junction of cylindrical - radial waveguides, (1 - R_s=0; 2 - R_s=R_{sm}); curves 3 and 4 - junction of cylindrical - rectangular waveguides, (3 - R_s=0; 4 - R_s=R_{sm}); curves 5 and 6 - junction on rectangular waveguides (5 - R_s=0; 6 - R_s=R_{sm})

Comparative difference of the found factors of dielectric losses with $\mathrm{tg}\delta$ determined by other methods has made 10-30%. It is connected first of all by that comparison was carried out with integrated values $\mathrm{tg}\delta$ (average on all volume of the sample).

In the considered structures the measurements of local losses were carried out, because only the region of waveguide coupling (region I) is resonant. Other regions of junction are cut-off for all types of modes on resonant frequency and their influence (as shown in works [9-11]) is minimal.

III. CONCLUSIONS

In rigorous formulation the electrodynamic and also numerical analysis of eigen Q-factor of H-modes in semi-opened waveguide junctions of cylindrical-radial waveguides and rectangular-rectangular waveguides with dielectric depending on dielectric permittivity, factor of dielectric losses, losses in waveguide walls and the geometrical sizes of structure was carried out. The comparative analysis with the similar results received earlier for waveguide junctions of cylindrical-rectangular waveguides was executed. Numerical researches have shown:

- the best quality the junction of cylindrical-radial waveguides. In such structures made of copper, or covered by precious metals it is possible to measure the electric parameters of cylindrical and plane samples with the factor of dielectric losses within the limits of $\mathrm{tg}\delta \approx 8 \cdot 10^{-5}$;

- the next high-quality type of junction the junction of cylindrical-rectangular waveguides. In such structures on H_{01n} -mode it is possible to carry out measurements of samples both cylindrical, and rectangular form of cross-section with the factor of dielectric losses within the limits of $\mathrm{tg}\delta \approx 1 \cdot 10^{-4}$;

- junctions on the basis of rectangular waveguides are intended for measurement of dielectric parameters in the form of rectangular parallelepipeds with the factor of dielectric losses $\mathrm{tg}\delta \approx 1.2 \cdot 10^{-4}$.

All types of waveguide junctions are intended for measurement of local dielectric losses in samples without their destruction because only the region of waveguides coupling is resonant. All waveguides are cut-off for all types of modes on resonant frequency and their influence is insignificant.

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