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MICROWAVE/RF SENSORS FOR COMPOSITION CONTROL OF CONTINUOUS FLOWS.

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Abstract - **Results of numerical investigation of complex propagation constants in circular multilayer waveguides are presented. A model is based on characteristic equation given in algorithmic manner and one can yield the complete spectrum of the waveguides in question. As a result of the investigation the novel type of RF/microwave evanescent mode sensors is suggested. These sensors can be used for composition control of continuous flows and have been applied for composition control of oil flows in well pipes.**

1. Introduction

Microwave/RF sensors are widely used in industry for measurement of material properties and composition control [1]. Petroleum industry is one of the fields where microwave/RF sensors play exceptionally important economi role. In this area of application the working principles and sensor design are very diverse. Again the measurement of material properties in pipe streams is the important application of microwave/RF sensors. Due to such application following demands are generally imposed on the sensors:

- geometrical configuration of a sensor must be suitable to measure streams in pipe;
- it is desirable that a sensor allows to use relatively inexpensive test equipment;
- reliability of the sensors operating in stream with high pressure and at presence of abrasive particles, as it takes place at pipes of well, is very important.

Sensors, in the form of a circular layer waveguide section, for composition control of continuous flows are described in this paper. One type of these sensors with the above mentioned geometry are waveguides operating at evanescent mode in wide frequency band and the other ones are sensors representing itself the partially filled resonant cavity.

In [2-4] circular multilayer waveguides with a perceive-constant dielectric filling were suggested as a sensing devices for permittivity control of real materials and flowing substances. Investigations of the question presented in [5-6] have shown that sensors designed in the form of section of the multilayer waveguides operating at evanescent mode can be suitable for composition control of a stream at wide frequency band and satisfy the above mentioned demands, when permittivity of the stream changes from 1 up to 100.

2. Model Foundation of the Sensors

A field model of the waveguide type of the sensors is the circular axis-symmetrical waveguide with free numbers of dielectric layers. In general case the complex permittivity and the complex permeability of each layer are represented by tensors of rank two with complex elements. The choice in a favor of this representation with bi-gyrotropic layers is caused by its universal representation [6].

In general case of a bi-gyrotropic waveguide filling, the field in the waveguide cannot be expressed by a linear combination of E and H modes. Longitudinal components of the field may be given by system of four power series having different powers as follows

$$E_z(\rho), H_z(\rho) \sim \sum_{i=1}^{4} C_i \sum_{k=0}^{\infty} A_k(\lambda_i)\rho^{k+\lambda_i} \qquad (1)$$

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where C_i are integral constants, determined by boundary condition; λ_i are power in the series determined by following

$$\lambda_{1,2} = \pm n\sqrt{\varepsilon_\varphi / \varepsilon}\ ;\ \lambda_{3,4} = \pm n\sqrt{\mu_\varphi / \mu} \tag{2}$$

where n is the number of field variations at azimuth direction; ε, ε_φ, μ and μ_φ are diagonal components of permittivity and permeability tensors, respectively. Azimuth and radial field components are determined by the longitudinal components and its derivations on radius [5].

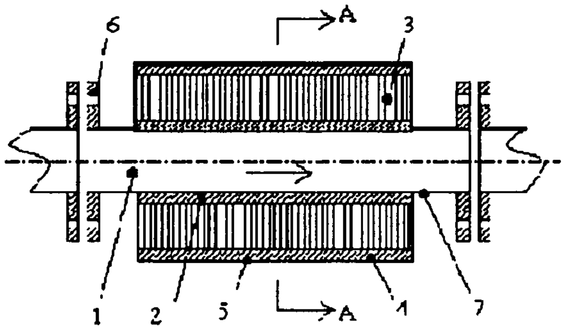

Fig. 1. Outline of the E_{01} evanescent mode sensor. 1 is the inner layer filled by a flowing MUT. 2, 3, 4 are the solid dielectrics. 5 and 7 are metal shield. 6 is the flange.

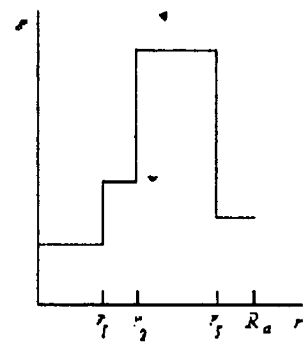

Fig. 2. Perceive-constant dielectric filling on radius of waveguide. R_a denotes the radius of a waveguide metal shield and r_1 denotes the radius of the inner layer.

Using expansions (1) and boundary conditions at layer surfaces ($\rho = \rho_i$), for tangential components one leads to four systems of algebraic equations

$$\sum_{i=1}^{4} C_{i,l,\xi} \sum_{k=0}^{\infty} A_{k,l,\xi}\, \rho_l^{k+\lambda_{i,l}} = \sum_{i=1}^{4} C_{i,l+1,\xi} \sum_{k=0}^{\infty} A_{k,l+1,\xi}\, \rho_l^{k+\lambda_{i,l+1}} \tag{3}$$

where ξ=z, φ. Applying (3) for each surface between layers and for metal surface of the waveguide one yields system of 2(2N-1) equations. This system is the math model for field phenomena in the multilayer waveguide. Equating the determinant of the above 2(2N-1) system to zero one can obtain characteristic equation needed.

Boundary condition at waveguide surface allows to present the field in the layer contacting with the metal shield of the waveguide using only two unknown constants. It follows that the boundary conditions for the interface between N and N-1 layers are written as

$$\sum_{i=1}^{2} C_{i,N,\xi}\, \Phi_{i,N,\xi}\left(\rho_{N-1}, s_N^e, s_N^m\right) = \sum_{i=1}^{4} C_{i,N-1,\xi}\, \Psi_{i,N-1,\xi}\left(\rho_{N-1}, s_{N-1}^e, s_{N-1}^m\right) \tag{4}$$

where ρ_{N-1} is the interface radius, $\Phi_{i,N,\xi}$ and $\Psi_{i,N-1,\xi}$ are tangential components of electric and magnetic fields in the N layer, contacting with the waveguide metal shield, and ones in the N-1 layer, respectively. As a result the field in N-1 layer is expressed with two unknown constants only. Applying the procedure above to other layers the field in inner layer is obtained by recurrent relations as follows

$$\Psi_{z2} = \sum_{i=1}^{2} C_{i,1} a_{1,i}^{\bullet};\quad \Psi_{\varphi 2} = \sum_{i=1}^{2} C_{i,1} a_{3,i}^{\bullet} \tag{5}$$

Coefficients $a_{j,p}$ (j = 1,...4; p = 1,...6) in any layer numbered as l produce the matrix with elements obtained by iterative transformations [5].

As a result of the model used, the characteristic equation is given in algorithmic manner, which is unchanged when the number of layers in a waveguide is varied. It is caused by the fact that the basic

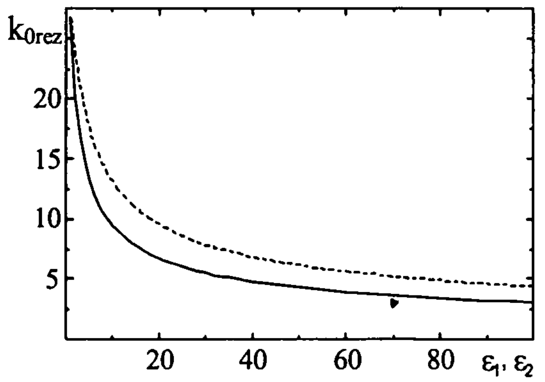

Fig. 3. Cutoff frequency of quasi- E_{01} mode in dependence on a layer permittivity of the circular two-layer waveguide filling.
The solid line corresponds to the inner layer permittivity changed and the dotted one corresponds to the outer layer permittivity changed.
For each line, layer, the permittivity of other layer is set 1. $r_1 / R_a = 5/9$.

computing procedures in the model represent the iterative transformations relating the data of nearby layers only.

A sensor in question itself represents the section of a circular waveguide with perceive-constant axis-symmetrical dielectric filling, Fig. 1 and Fig. 2. In dependence of operating frequency this section is unregular waveguide, reactive attenuator or resonator. The sensors in the form of partially filled cylindrical cavities are well suited for measurements of liquids [7].

Fig. 3 illustrates opportunity to apply above section as resonator at quasi-E_{010} mode. From Fig.3 one can see that, at given dimensions, best resolution on resonant frequency takes place for lower permittivity values of a material under test (MUT).

Opportunity to use the sections as reactive attenuator for composition control of a MUT can be seen from Fig.4. to Fig. 9. Results of numerical investigation of circular two-layer waveguides beyond cutoff with perceive-constant dielectric filling for quasi-E_{01} mode are presented in these figures. Relation between waveguide radius and radius of inner dielectric filling is set to achieve maximum sensitivity for the imaginary part of the propagation constant (attenuation due to the evanescent mode condition) in dependence on MUT permittivity. Again Fig. 4 and 5 show that for a given MUT the better sensitivity can be achieved for the layer waveguide in comparison to waveguide filled uniformly.

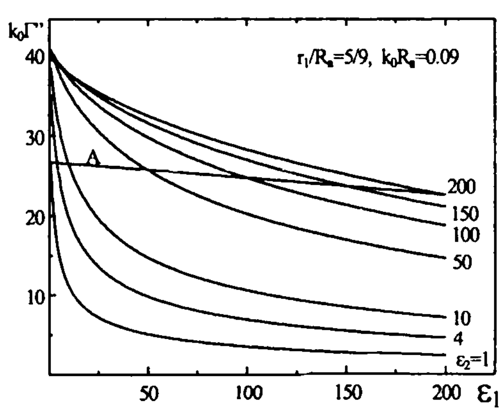

Fig. 4. The imaginary part of propagation constant, $k_0\Gamma''$ versus the inner layer permittivity ε_1 for two-layer circular waveguide beyond cutoff at quasi-E_{01} mode.

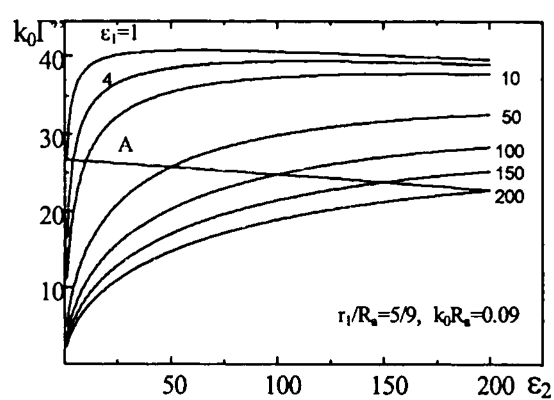

Fig. 5. The imaginary part of propagation constant, $k_0\Gamma''$ versus the outer layer permittivity ε_2 for two-layer circular waveguide beyond cutoff at quasi-E_{01} mode.

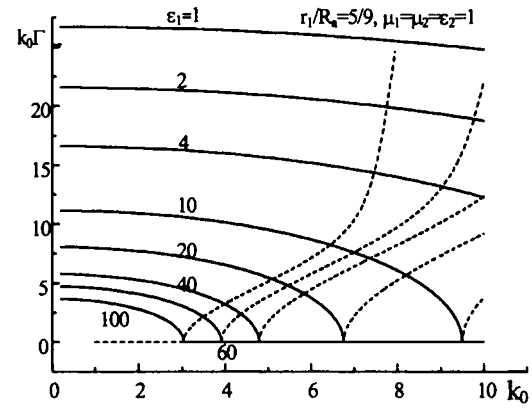

Fig. 6. Propagation constant for quasi-E_{01} mode in two-layer circular waveguide versus frequency in dependence on the inner layer permittivity ε_1. Solid lines denote the attenuation constant, the evanescent mode condition, and doted lines denote phase constant, the mode propagating.

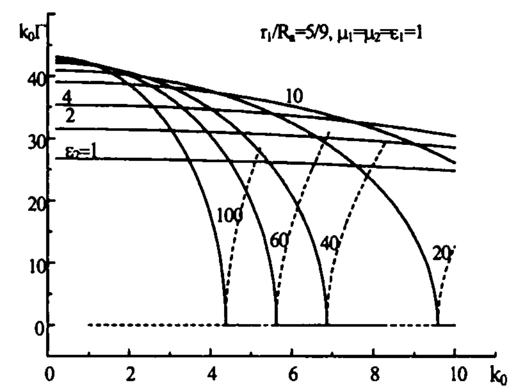

Fig. 7. Propagation constant for the quasi-E_{01} mode in two-layer circular waveguide versus frequency in dependence on the outer layer permittivity ε_2. Solid lines denote the attenuation constant, the evanescent mode condition, and doted lines denote phase constant, the mode propagating.

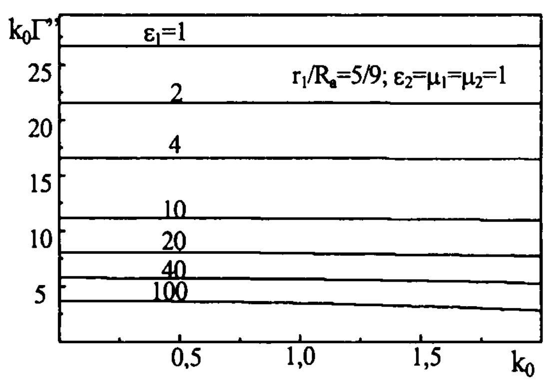

Fig. 8. Attenuation constant of the quasi-E_{01} mode versus frequency beyond cutoff.

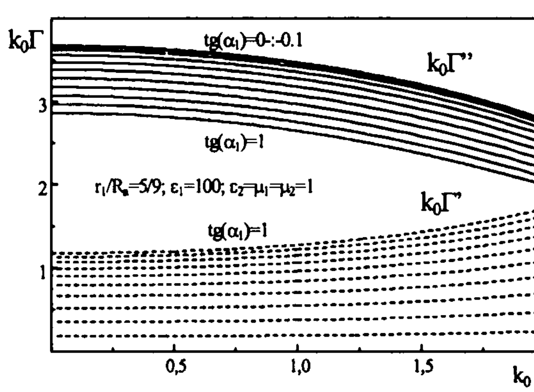

Fig. 9. Attenuation constant, solid lines, and phase constant, dotted lines, of the quasi-E_{01} mode beyond cutoff with respect to losses in a MUT being the inner dielectric layer.

Data presented at Fig. 6 and 7 illustrate that using the inner layer for a MUT provides the wider operating frequency band in comparison to outer one. Fig. 8 and 9 illustrate frequency characteristic of the two-layer waveguide. It is seen that for the dimensions set the attenuation constants are very slowly depended on frequency in wide band. The data presented show that wide-band sensors can be designed on the basis of the mode and the waveguides discussed above.

3. Application of the Sensors for Composition Control

As an illustration to apply the sensor in the form of E_{010} cylindrical resonant cavity for composition control of industrial liquids, measurement of ethyl alcohol solutions and gasoline A92 with different water contents were carried out. Above MUT were adjusted at the axis of transmission coupled sensor, having resonant frequency of 3GHz without MUT in glass containers. Measured quantities of the sensor were resonant frequency, bandwidth and insertion loss. Sensitivity of these quantities in dependence on change of water concentrations was observed. To estimate the resolution of the sensor it was used that

$$\Delta N_f[\%vol.] = \left(\frac{df_{res}}{dN}\right)^{-1} \Delta f_{res}; \qquad \Delta N_\alpha[\%vol.] = \left(\frac{d\alpha}{dN}\right)^{-1} \Delta\alpha \tag{6}$$

where $\Delta N_f[\%vol]$ and $\Delta N_\alpha[\%vol]$ denote resolutions on water contents using resonant frequency f_{res} and insertion loss α, respectively; Δf_{res} and $\Delta\alpha$ denote measurement errors of respective quantities, which are determined by measuring equipment; fractions in parentheses represent itself sensitivity of measured quantities, obtained from experiment data and depended on the MUT and the sensor.

For ethyl alcohol solutions with water concentrations varied from 0 up to 4 % vol. the setup provided the measurement error for resonant frequency Δf_{res} of ±0.3MHz and resolution for insertion loss $\Delta\alpha$ of ±0.2dB. It gives resolutions on water contents about ±1.2 %vol. using the resonant frequency as control parameter, and resolutions on water contents about ±0.9 %vol. using insertion loss as control parameter. Measurement setup with Δf_{res} of ±10 kHz and $\Delta\alpha$ of ±0.01dB would provide the resolutions on water contents about ±0.04 %vol. for the resonant sensor.

For gasoline-water mixtures with water being from 0 up to 26 % vol. the setup with Δf_{res} of ±1MHz and $\Delta\alpha$ of ±0.2dB was used. It gives the resolutions on water contents about ±0.5 %vol. Measurement setup with Δf_{res} of ±10 kHz and $\Delta\alpha$ of ±0.01dB would provide the resolutions on water contents for the sensor about ±0.004 %vol. using the resonant frequency as control parameter and resolutions on water contents about ±0.02 %vol. using insertion loss as control parameter.

Based on the investigations described in part II of the paper the sensors were designed in the form of evanescent quasi-E_{01} mode waveguide section with two layers. Outline is Fig. 1. Inner layer is a liquid MUT flowing through the sensor. These sensors were used as a reactive attenuator operating in deep cut-of conditions. Damping the influence of H_{11} mane mode was achieved by design and adjusting of coupling elements [2]. Also a remaining influence of the H_{11} mode is removed by the calibration procedure due to weak dependency of attenuation of this mode on MUT permittivity.

Testing of the waveguide sensors have been carried out at mouths of oil wells for oil-water mixtures with water contents changing from 0 % to 100 %. Relative permittivity of these mixtures varied from 2 to 80. Sample of a sensor was adjusted as section of a pipeline. The sensors have been manufactured in the form of two-layer circular waveguide section with length of 700 mm, radius of 180 mm and radius of the inner hollow cylinder being of 100 mm. The inner hollow cylinder continued the pipeline and did not distort the oil-water flows measured. Two coupling elements were adjusted at distance of 300 mm from each other in the dielectric layer. Operating pressure varied from 0 to 4 MPa. Temperature of flows varied from 0 ^{0}C to 70 ^{0}C.

Insertion loss of the sensors with MUT flowing through was measured. Procedure for composition control of oil-water mixtures using these sensors is described in [6]. Comparing the measurement results obtained by the sensors with data obtained by chemical analysis it have been yielded that the waveguide sensors can provide the water content determination in the above conditions with measurement error about 5 % vol.

4. Conclusion

The sensors described above are well suited for measurement of flows in pipes. Equipment providing the amplitude measurement is sufficient to use with the sensors. The sensors have the similar geometry, operate at the same wave mode and permit the same MW measuring circuits to be used. It allows to design sensors representing in a single form, in dependence on operation frequency, the reactive attenuator or the resonator. The former characterized by wide band frequency operation senses basically the change of a MUT permittivity, the latter having high resolution reacts for change of permittivity and losses in MUT. Application of such dual sensors can improve validity and precision of composition control of industrial flows.

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