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Microwave Components as Functional Elements for Industrial Sensors

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Abstract. Application of various passive microwave components as functional elements of industrial sensors is considered. Among these microwave components are: cut-off waveguides, open resonators, polarization-sensitive wire reflectors, etc. Design of such microwave sensors is illustrated by examples covering measurement of some technological parameters.

1. Introduction
Microwave sensors are effective for monitoring of technological parameters in many industries [1–3]. Their design is based on the use of microwave components: waveguides, resonators, antennas of various types. Specific peculiarities of solved problems influence on the choice of appropriate microwave components for the realization of sensors, of sensors’ informative parameters.

Many actual measurement problems may be solved through application of other microwave components for realization of industrial sensors. Design examples of such components-based sensors for some industrial applications are considered in the paper. Among these microwave components are: cut-off waveguides, open resonators, polarization-sensitive reflector-based microwave sensors, etc.

2. Cut-off waveguides-based sensors
Electromagnetic waves propagate in a waveguide if operating frequency \(f\) exceeds critical frequency \(f_c\) (\(f > f_c\)) for oscillations of a type excited in this waveguide, for instance of \(H_{11}\)-type in a hollow circular waveguide. If \(f < f_c\) then cut-off regime takes place. In this case electromagnetic wave doesn’t propagate along a waveguide and a reactive evanescent electromagnetic field exists. It attenuates exponentially with the increase of a distance \(z\) to a coupling element for excitation of oscillations and is characterized by attenuation constant \(\alpha\): \(\alpha = 2\pi \sqrt{\varepsilon \mu / c} \sqrt{f_c^2 - f^2}\) where \(c\) is velocity of light, \(\varepsilon\) and \(\mu\) are dielectric permittivity and magnetic permeability of a substance in the waveguide, respectively.

By choosing parameters of a cut-off waveguide and frequency of electromagnetic wave, microwave sensors can be designed. Their characteristics can be varied, in particular by the following ways: 1) cavity resonators and transmission lines may have discontinuous metal surfaces; it is done by connecting section(s) of cut-off waveguide to a cavity; opposite ends of these waveguides are open and are outside or inside the cavity; in this case metal surface may have only less than 20 percents of the whole cavity surface; 2) volume of a cavity occupied by electromagnetic field, may be increased or decreased through insertion section(s) of cut-off waveguide into the cavity or its (their) removal from
this cavity; an added/removed volume containing possibly an object with some permittivity and geometrical parameters, may be as cut-off waveguide itself or may be connected to the initial volume through a cut-off waveguide; such waveguide section(s) may be inside the cavity or at its surface.

The following applications of the designed cut-off waveguides-based sensors may serve as examples: level sensors for liquid substances (Figure 1, a and Figure 1, b), in particular of liquid metal in open reservoirs; dielectric permittivity-independent level sensors for level dielectric liquids; physical parameters (density, concentration, etc.) of substances flowing in pipelines (Figure 2); contactless sensors of inner diameter of metal tubes (Figure 3) and deep holes in metal objects.

Section of a metal tube (cut-off waveguide) is connected to the open end of a metal reservoir where level of a liquid is measured. This metal tube is open at the opposite end in order not to prevent needed operations during a technologial process, for instance of filling in the reservoir by a monitored liquid; it can be molten metal while the reservoir is crystallizer of continuous casting installation. It can have rectangular (Figure 1, a) or circular (Figure 1, b) form. Electromagnetic oscillations are excited in the reservoir that is resonant cavity where changeable level of a liquid determines resonant frequency of electromagnetic oscillations of the cavity. Cut-off waveguide may be metal tube of small height (~ 20 ÷ 100 mm) and the cross-section smaller than that for the reservoir’s cross-section. Experiments confirm calculated data, for instance for excitation of electromagnetic oscillations of $H_{101}$-type in a rectangular metal cavity and of $H_{111}$- and $H_{011}$-types in a circular metal cavity. So, measurements of a conductive liquid level were done for the circular reservoir with diameter of 98 mm, height of cut-off waveguide of 75 mm, its diameter of 75 mm. Oscillations of $H_{111}$-type were excited in the reservoir; coaxially spaced in the reservoir metal rod with the diameter of 20 mm imitated a jet of molten metal pouring into the reservoir. Resonant frequency was changed within the range 1.6 ÷ 1.74 GHz if level was changed within the limits of 0.2 ÷ 1.0 m.

![Figure 1](image1.png)

**Figure 1.** Cut-off waveguide-based microwave sensors of liquid level in open reservoirs:
- a – rectangular reservoir; b – circular reservoir
- 1 – metal reservoir, 2 – metal tube with upper open end (cut-off waveguide), 3 – electronic unit, 4 – coupling element, 5 – intermediate area between reservoir 1 and metal tube 2, 6 – monitored liquid

Pipeline section itself may serve as cut-off waveguide sensor for measurement of physical parameters of a substance (Figure 2). In this case decaying (evanescent) electromagnetic field exist in the waveguide between excitation and pick up coupling elements. For a monitored dielectric liquid flowing through the pipeline registered amplitude $E$ of electric field at the pick up section is $E(e) = E_0 e^{-c|l|}$ where $l$ is distance between excitation and pick up coupling elements; $E_0$ is value of $E$ at the waveguide section with excitation coupling element; $e$ is dielectric permittivity of a liquid being function of a measured physical parameter, $\alpha = 2\pi\sqrt{\varepsilon}(f_0^2 - f^2)/c$ : $f$ is frequency of excited electromagnetic waves; $c$ is light velocity. So, if inner tube diameter is 100 mm, $l = 100$ mm, $f = 1$ GHz then $\alpha = 0.33\sqrt{\varepsilon}$ 1/cm; if $e$ is changed within the limits 1.8 ÷ 2.0 (oil, oil products, etc.) then relative change of $E/E_0$ is 17 % that is rather high value.
Measurement of inner metal tube diameter in a contactless way is needed both under production of tubes and testing of ready items. Cut-off waveguide-based microwave sensor of inner tube diameter is shown in Figure 3. Hollow metal tube is introduced into the monitored tube. This tube has changed (increased as it is shown in the figure or decreased diameter) at the measuring area; neighbouring parts of this tube are cut-off waveguides for resonant frequencies of electromagnetic oscillations excited in the resonant cavity that is the volume of a measuring area. Oscillations are excited via coupling element at the end of connecting cable located inside the hollow tube; other end of the cable is connected to the electronic unit for excitation of electromagnetic oscillations and measurement of resonant frequency being function of measured inner tube diameter. So, oscillations of $H_{m1p}$-type ($m = 1,2, \ldots; p = 1,2, \ldots$) can be excited in the resonant cavity shown in Figure 3. For the lower $H_{111}$-type critical frequency is $f_c = \frac{c}{m\pi(R_1 + R_2)}$. Here diameter $2R_1$ of the hollow tube within the measuring area exceeds its diameter $2R$ of other parts that are cut-off waveguides. Resonant frequencies $f_r$ of a waveguide section shortened at its ends are nearly equal to those of the above resonant cavity; they can be expressed so: $f_r = \frac{c}{\lambda_2^2 + (p/2l)^2}$, $p = 1,2, \ldots$, where $l$ is the length of the measuring section (resonant cavity). For instance, during centrifugal casting process of tubes’ production inner diameter $2R_2$ of tubes vary within $46 \div 58$ mm. If $l = 150$ mm, diameter of hollow metal tube $2R_1 = 10$ mm, resonant frequency $f_r$ is varied within the range of ~ $1.8 \div 2.7$ GHz for the excited $H_{111}$-type of oscillations.

3. Open microwave resonators-based sensors

Contactless sensors of a molten metal level in technological reservoirs of metallurgical industry can be realized on the base of Fabry-Perot microwave resonators. Surface of a molten metal serves as one of two metal mirrors. The second mirror is reflector – concave or flat metal mirror with diameter of 20-30 mm. High quality TEM$_{mnp}$-types of oscillations may exist in such an open resonator; microwave power is concentrated within a beam. Single-mode regime is in the resonator if only longitudinal TEM$_{00q}$-type ($q = 1,2,3,\ldots$) is excited. Measuring the number $N$ of natural oscillations in the resonator excited during the sweep of the wavelength $\lambda$ within the range $[\lambda_2 \div \lambda_1]$, distance $l$ to the monitored surface can be determined: $N = 2(1/\lambda_1 - 1/\lambda_2)l$. Inaccuracy of discrete level determination is $\Delta l = 1/2(1/\lambda_1 - 1/\lambda_2)$. For instance, if $\lambda_2 = 4$ mm, $\lambda_1 = 8$ mm then $\Delta l = 4$ mm; relative error is 0.4 % for the measuring range $l = 0 \div 1000$ mm. Value of measurement accuracy depends significantly on a wavelength sweeping range.

If a higher TEM$_{mnp}$-type (for instance, at $n > 20$, $m = 0$) is excited in microwave open Fabry-Perot resonator, then microwave power is absent in a rather large central part of the volume between the mirrors. Microwave power is concentrated as a set of narrow beams in a ring-like periphery part between the mirrors. Such property of the resonator gives ability to design resonators with absent
central areas (they can be removed from metal mirrors). Presence of an object in central part doesn’t influence on oscillatory characteristics of the open resonator. So, in metallurgy level of a molten metal in a reservoir (continuous casting mould, ingot mould, ladle, etc.) is one of important technological parameters. For example, if installation for continuous casting is considered then microwave sensor of a molten metal level in the crystallizer can be designed as the upper mirror of the open resonator without central part; surface of a molten metal in the crystallizer is the other mirror of the resonator (Figure 4). A jet of a molten metal flowing out from intermediate reservoir into the crystallizer through the upper mirror of the sensor, doesn’t influence on electromagnetic field of the open microwave resonator. Measuring the resonance frequency of electromagnetic oscillations of the resonator, level of a molten metal in the crystallizer can be monitored.

**Figure 4.** Open resonator-based microwave sensor of a molten metal level in an open reservoir.
1 – molten metal, 2 – crystallizer, 3 – metal mirror, 4 – jet of molten mirror, 5 and 6 – coupling elements, 7 – oscillator, 8 – electronic unit

Other applications of microwave open resonator-based sensors are: contactless measurement of metal and dielectric sheet thickness; of a distance to a metal surface at different technological installations including those where influence of their stable or movable parts on measurement results should be excluded.

4. Polarization-sensitive reflector-based microwave sensors
A couple of thin metal wires may serve as end reflectors of cavity/waveguide resonators instead of metal plates. Experiments showed that only 3 ÷ 7 thin wires used as end reflectors are enough in order to provide high quality factor of waveguide resonators. Forms of wires and their location across a waveguide should be similar to the direction of electric field lines of an oscillation mode excited in the resonator. Such polarization-sensitive wire reflectors do not keep modes with other electric field pictures. Examples of application areas of such approach are: 1) measurement of level of a substance in a tank; in this case several wires are located at the surface of an open metal tank being thus microwave cavity resonators; 2) measurement of physical parameters (density, concentration, etc.) of liquids in pipelines; flowing-through waveguide resonator is designed by a section of metal waveguide (or pipeline itself) and two metal wire polarization-sensitive reflectors installed across the waveguide at the ends of the section; these reflectors doesn’t disturb significantly a liquid flow through a pipeline.

Example of such an arrangement of microwave sensor for measurement of a molten metal level in a reservoir is shown in Figure 5. Here sensor construction doesn’t disturb technological process including presence of the jet of a molten metal at the open surface of a reservoir. In this case resonant cavity represents the volume restricted by the lateral sides of the metal reservoir, the surface of a molten metal and the set of metal wires at the open end of the reservoir. Resonant frequency of electromagnetic oscillations of the cavity is function of a molten metal level.
Figure 5. Polarization-sensitive reflector-based microwave sensor of a molten metal level in an open reservoir.  
1 – metal reservoir, 2 – a molten metal, 3 – metal plate, 4 – metal wires, 5 – coupling element, 6 – jet of a molten metal

5. Conclusion
The above-considered approach covers only examples of application of passive microwave components for the design of industrial microwave sensors. Other microwave components may be also effectively applied for this purpose and many actual measurement problems may be solved.

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