

A Microwave Sensor for Evaluation of Plastic Wall Thickness

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Introduction

Non destructive measurement of the thickness and monitoring its variation of lossy dielectric slab products is of great interest in many facets of industry. Methods are based on measurements of transmitted and/or reflected electromagnetic power from a dielectric material under test by an incident electromagnetic wave. The recorded amplitude and phase of the transmitted or reflected wave is analyzed and processed to create appropriate correlations with physical and/or dimensional variations of a material.

Many techniques (transmission/reflection line, free space, open ended coaxial or waveguide probe) have been developed to measure these properties such as techniques in time domain or frequency domain with one port or two ports, etc. Every technique is limited to specific frequencies, materials and applications [1–3]. However, in some industrial processes used materials have a low permittivity or high loss; opposite wall is not metal-backed and only one side of materials is accessible. Reflectivity signal from the opposite wall is low, these methods unsuitable in industry. Resonant measurements are the most accurate. To reduce the sensor size, it is appropriate to use the resonance properties of microstrip antennas [4]. The lightweight construction and the suitability for integration with MICs (Microwave Integrated Circuits) are two more of their numerous advantages. Microstrip printed antenna technology is suitable for low cost manufacturing. This is important, since MICs are much easier to handle and less expensive than the alternative waveguides.

Suitability of microstrip antennas for low-frequency applications have been demonstrated in [5]. Although microstrip antennas are widely used, there is a little research on the design of near-field microstrip antennas for evaluation of plastic wall thickness and monitoring its variation for industrial applications.

Theory

The relative complex permittivity of an isotropic material is dependent on several variables, such as

frequency, temperature, density, and moisture content. From a view of slab thickness measurement, these variables must be fixed or appropriate correlations must be established. The loss factor, is often used to study the structure and composition of materials. The depth of penetration d of microwaves into a dielectric is a function of the total dielectric loss tangent and the vacuum wavelength λ_0 [6]

$$d = \frac{\lambda_0}{\pi \sqrt{\varepsilon_r' \tan \delta}}, \quad (1)$$

where ε_r' is the real part of dielectric permittivity ε_r , $\tan \delta$ is the total dielectric loss tangent, $\varepsilon_r' \tan \delta = \varepsilon_r''$ – imaginary part of dielectric permittivity.

Microwave has been low dept of penetration inside Carbon Fibre Reinforced Plastics (CFRP) and results from measurement can be ambiguous to interpret. Lower frequency wave penetrates deeper (Fig. 1). However, the size of the antenna increases and the resolution degrades rapidly.

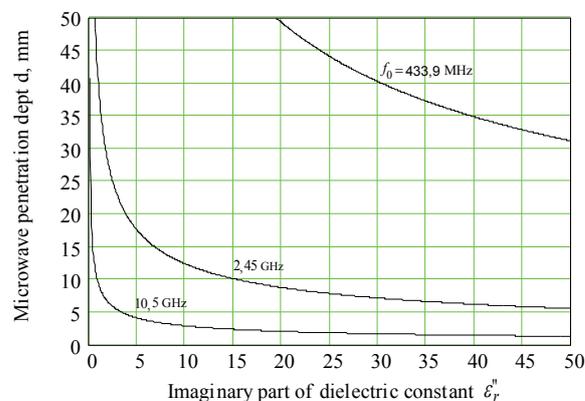


Fig. 1. The depth of penetration of microwaves into a dielectric

Problem can be solved using a substrate integrated waveguide antennas or low-frequency microstrip antennas

[5]. The substrate material (filler) is selected with the nearest dielectric permittivity as the measurement slab. The fillers can significantly reduce the frequency of operation and keeping the small size of antennas, reducing reflection from a measurement wall, increases the penetration depth, maintains the resolution, and increasing the detection sensitivity and measurement accuracy. Polarizability of microwave signals enables the study of fiber bundle orientation or misalignment during manufacturing and provides information about cut or broken fiber bundles. To eliminate the influence of anisotropy for wall thickness measurement should be used microwaves of circular polarization.

Assuming a perpendicular plane wave traveling through a layer of low-loss material ($\epsilon'' \ll \epsilon'$) with thickness h , the real and imaginary components of the relative complex permittivity are determined as follows [2]:

$$\epsilon' \cong \left(1 + \frac{\Delta\Phi \lambda_0}{2\pi h} \right)^2, \quad (2)$$

$$\epsilon'' \cong \frac{|\Delta A| \lambda_0 \sqrt{\epsilon'}}{8.686 \pi h}, \quad (3)$$

where $2\pi m \leq \Delta\Phi \leq 2\pi(m+1)$ is the phase shift; $m = \text{trunc}(h/\lambda_0)$ – the integer part of h/λ_0 ; ΔA is the attenuation in decibels.

Eq. (2) shows that phases information is necessary to determine the sample thickness h , when is known the numerical value ϵ' . At a given frequency, sample thickness should fall within the following interval [3]

$$m \frac{\lambda_0}{\sqrt{\epsilon_r'} - 1} \leq h \leq \frac{\lambda_0}{\sqrt{\epsilon_r'} - 1} (m+1), \quad (4)$$

where m is an integer to be determined.

In any industrial process control, the phase ambiguity problem has to be solved in a way that can be easily automated. If a dielectric slab thickness

$h \geq \lambda_0 / \left(\sqrt{\epsilon_r'} - 1 \right)$, the integer m can be determined as

well as Nicholson–Ross–Weir conversion technique by analysis of group delay. Delay through the material is a function of the material total length and can be used to resolve this ambiguity. Measurements at two different frequencies can also be used to solve the phase ambiguity problem [2, 3].

For one side thickness measurement, wave reflected from the opposite side must pass the same distance as the incident wave. If the incident wave propagation vector is perpendicular to the dielectric surface, the penetration depth should be at least twice higher. In this case, better suited the patch antenna [4]. The fields at the end of the patch can be split into tangential and normal components with respect to the ground plane. Normal field components create only near field. Their contribution to the far field in broadside direction cancels each other. The tangential field components, which are in phase, combine to give the

maximum radiated field normal to the surface of the patch, create far field and penetrate into a dielectric deeper. Normal and tangential fields are complementary for sensor applications and allow measurement from low to highest thickness.

Sensor design

To measure the thickness and properties of the low permittivity or high loss composites, when only one side of materials is accessible, most suitable are microstrip antennas. They are narrowband antennas compared to conventional microwave antennas, since the radiation is a consequence of a resonance [4]. For resonant measurement antenna (sensor), a special feeding technique (proximity coupling) was used. This antenna uses electric and magnetic coupling, in which no physical connection is made between the feed line and the dipole [7]. Proximity coupled microwave thickness sensor antenna have many advantages over end fed and coaxial fed antenna. Some advantages include: no galvanic contact between feed line and radiating element, low permittivity patch substrate with a large thickness, no drilling required, less spurious radiation, better resonance sensitivity.

The antenna (Fig. 2) consists of two stacked substrates 3, 4 with a ground plane 5 underneath and two collinear microstriplines 1, 2 at different levels. The feed line 2 is located between the two substrates and overlaps the dipole 1, located on top of the substrate 3.

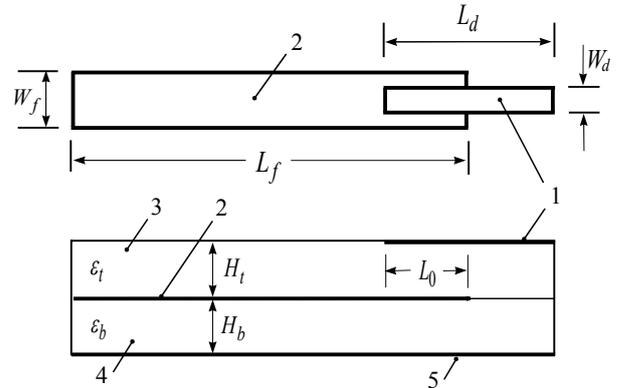


Fig. 2. The experimental proximity-fed antenna geometric: 1 – dipole; 2 – feed line; 3 – top substrate; 4 – bottom substrate; 5 – ground plane

The theory behind proximity feed patches is quite complex and only design guidelines will be presented [7].

ANTENNA MAGUS[®] – antenna design software could easily calculate specifications (geometric dimensions, effective dielectric permittivity, return loss and attenuation). Final corrections are then made for coupling from numerical evaluation with CST MICROWAVE STUDIO[®] (CST MWS). Tune the length variable of the patch antenna in the model such that the tuned patch radiates at the desired frequency. Tune the patch overlaps distance in the model such that the patch will give maximum parallel resonant quality. Geometric dimensions and parameters of the experimental proximity-fed antenna are given in Table 1.

Table 1. Geometric dimensions and parameters of the experimental proximity-fed antenna

Centre frequency	f_0	2,45 GHz
Input impedance (at f_0)	Z_0	50 Ohms
Dipole length	L_d	49,7 mm
Dipole width	W_d	12,5 mm
Feedline length	L_f	108 mm
Feedline width	W_f	18 mm
Overlap length	L_0	25 mm
Top substrate height	H_t	6,5 mm
Top substrate relative dielectric permittivity	ϵ_t	1,03
Bottom substrate height	H_b	3,2 mm
Bottom substrate relative dielectric permittivity	ϵ_b	2,35

The antenna radiation characteristic at centre frequency is shown in Fig. 3.

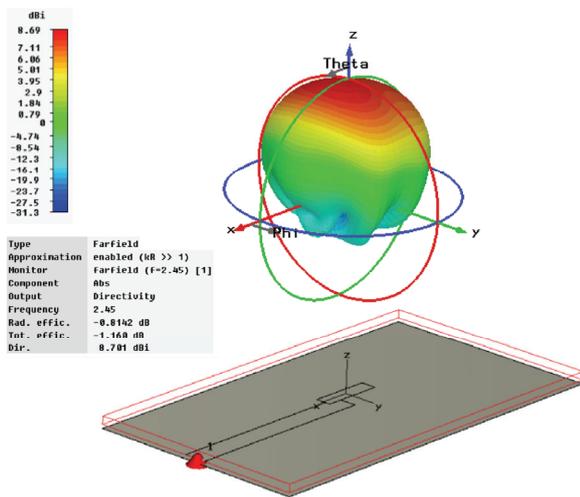


Fig. 3. Antenna radiation characteristics at centre frequency

The approach here is based on the idea that for sensing applications exploited resonance properties of this antenna.

An equivalent circuit of the antenna shown in [7]. The coupling capacitance between the feed line and the patch is a distributed element, which with feed line and equivalent shunt capacitance and inductance of patch forms transmission line resonator (TLR) circuit. Input impedances of low-loss transmission line resonators are generally expressed in terms of transcendental functions, so it is difficult to quantify analytically. CST MWS allows to evaluate impedance and admittance of TLR in broad frequency range. Fig. 4 shows the field distributions at feed line (the TLR surface) as some resonant states of $n = 1, 2, 5$ for comparison.

A change in the permittivity of the patch environment causes a change in its capacitance and hence a shift of the resonator frequency. This circumstance allows to evaluate the thickness of the high loss composites via recording of resonant frequency or phase deviation.

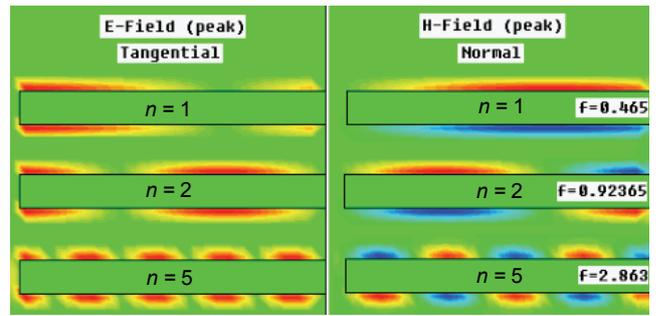


Fig. 4. Electric and magnetic-field distribution on the feed line at TLR resonant states of $n = 1, 2, 5$

The input impedance and admittance of TLR circuit in frequency range 2 to 5 GHz are shown in Fig. 5. As we can see in Fig 5 in frequency range 2 to 5 GHz gets tree shunt (a) and two series (b) resonance. Maximum shunt non-loaded resonance quality is 1150 at 2,863 GHz. Additional investigation showed that the lowest shunt resonance occurs at 0.92365 GHz. At this frequency, real part of impedance $Z = 7100$ Ohms and non-loaded resonance quality are 1050.

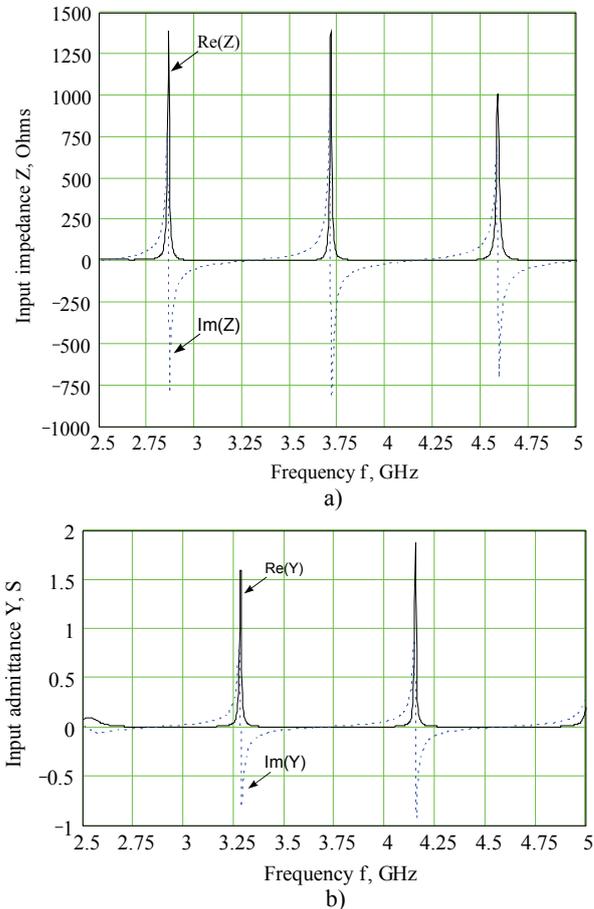


Fig. 5. Input impedance (a) and admittance (b) of TLR circuit in broad frequency range

For sensing applications, due to high quality most suitable shunts resonance of TLR. In order to increase patch tangential electric field component influence, TLR shunt resonance operating frequency area must be close as possible to antenna center frequency.

Sensor substrate materials

The most critical parameter for patch antennas is the dielectric permittivity, which must be controlled to within $\pm 0,2\%$ to achieve a resonant frequency accuracy of $\pm 0,1\%$. [8]. The top substrate must be made with a lower permittivity to produce loosely bound fringing fields, yielding better radiation and increases the sensitivity. For a foam substrate, there is no surface-wave excitation losses and higher efficiency are obtained by making the substrate thicker. A higher value of permittivity of bottom substrate causes tightly coupled field, that don't produce spurious radiation. After analysis, the most appropriate materials for top and bottom substrate of proposed microwave sensor are presented in the Table 2 and 3.

Table 2. Extremely low dielectric permittivity foam materials for the top substrate of experimental proximity-fed antenna

Top substrate material	ϵ_r	$tg\delta$	T_{max} , $^{\circ}C$	WA , %
Polyurethane foam block	1,04–1,25*	0,001–0,005*	135	3–1*
Cross-linked hydrocarbon closed cell foam block	1,03; 1,06	0,0001	85	0,04
ROHACELL® 31 HF	1,05	<0.0002	130	–

Note: * – depending on density; T_{max} – maximum continuous operating temperature; WA – 24-hour water absorption.

ROHACELL® 31 HF at Evonik Industries AG is a 100 % closed-cell rigid foam plastic based on PMI (Polymethacrylimid) with a fine cell, excellent bonding properties, extremely low dielectric permittivity and particularly favorable transmission properties in the high-frequency region. Owing to its excellent creep compression resistance (dimensional change under the influence of pressure and temperature), ROHACELL® 31 HF is ideally suited for microwave sensors in industry and allows measurements under hostile environments and relative high temperatures.

Table 3. High frequency laminate for the bottom substrate of experimental proximity-fed antenna

Laminate (bottom substrate)	ϵ_r	$tg\delta$	T_{max} , $^{\circ}C$	WA , %
Rogers RT/duroid® 5870	2,33	0,0005 – 0,0012	150	0,02
Rogers RT/duroid® 5880	2.20	0,0004 – 0,0009	150	0,02

Rogers RT/duroid® 5870 and 5880 high-frequency laminates at Rogers Corporation are PTFE composites reinforced with glass micro fibers. They have the lowest dielectric permittivity and loss of any reinforced PTFE material, are isotropic, have uniform electric properties over frequency, extremely low water absorption characteristics and resistant to all solvents and reagents normally used in etching printed circuits or plating edges. Parameter stability in broad temperature range makes them well suitable for microwave sensor.

Sensor numerical evaluation

The CST MICROWAVE STUDIO® evaluation model of plastic slab thickness measurement is shown in Fig. 6. Measured variable depends mainly on slab materials, thickness, operating frequency and on the distance between the sample and the sensor (gap size). Dielectric properties over a temperature range of common plastics for numerical evaluation can find in [9].

To simplify the measurement at first there were only flat polypropylene plates with thickness d between 1 mm and 10 mm used. Sensor shunt resonant frequency was measured for various thickness and gap sizes h at several frequency ranges.

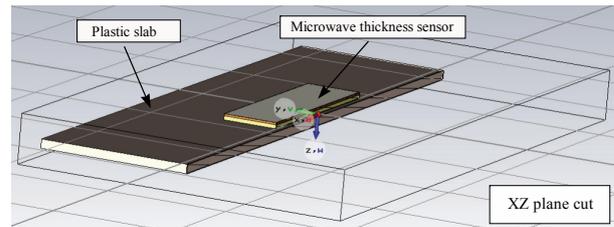


Fig. 6. CST MWS evaluation model of plastic slab thickness measurement

The best orthogonal behaviour was located in a frequency range of 2,8 GHz to 2,9 GHz when the opposite wall is free. The dielectric loading of sensor affects both its resonant frequency and impedance (Fig. 7).

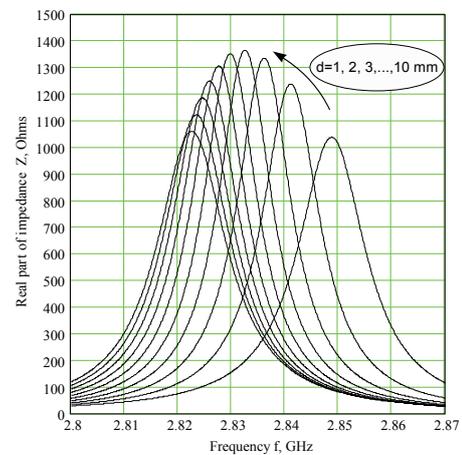


Fig. 7. Real impedance and resonance frequency variation versus on the polypropylene slab thickness d . Opposite wall is not metal-backed, gap size 0,1 mm

As the dielectric thickness of the substrate increases from 1 to 4 mm, the antenna shunt resonant frequency decreases from 2,849 to 2,833 GHz, which increases the real part of impedance Z from 1050 to 1375 Ohms. For thickness from 4 to 10 mm frequencies decrease more slowly to 2,823 GHz and Z decreases to 1065 Ohms. The following results focus on a measurement frequency of 2,8 GHz to 2,9 GHz, where the best results were achieved (Fig. 8 a). Similar measurements were also performed at frequencies of 4,5 to 4,7 GHz (Fig. 8 b).

As shown in Fig. 8 resonant frequency deviation of the polypropylene slab thickness variation is greater at lower operating frequency area. At higher frequencies, the

deviation is smaller. This confirms, that to increase the sensors sensitive need to select operating area closer to the center frequency of the antenna. Real impedance and resonant frequency are almost independent of boundary conditions on the other side of the plastic wall (Fig. 8, a).

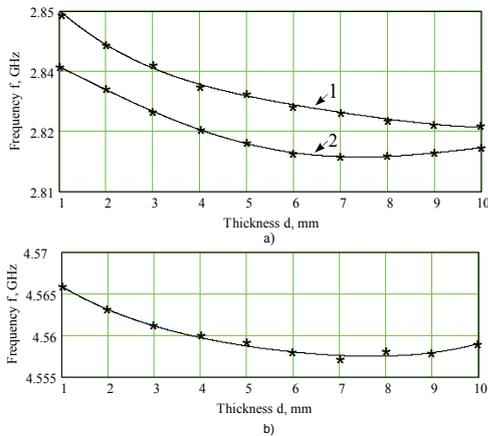


Fig. 8. Resonance frequency deviation versus of the polypropylene thickness variation: a – when the opposite wall is free (1) and metal-backed (2); b – at higher resonant frequencies, when the opposite wall is free. Gap size is 0,1 mm

During the measurement at manufacturing process is difficult to ensure a fixed minimal gap between the antenna and the measured object. To examine the accuracy of method, it is necessary to evaluate the influence of the gap to resonant frequency change. The influence of the gap size to resonant frequency is shown in Fig. 9.

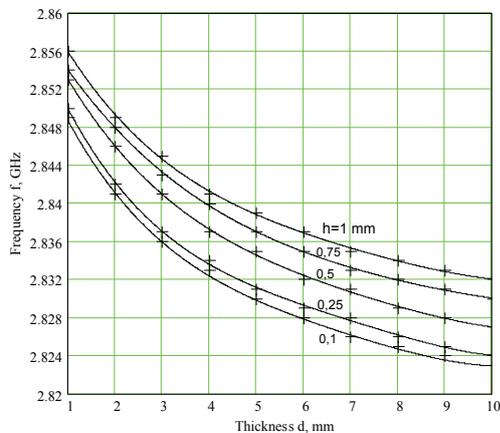


Fig. 9. Resonance frequency deviation versus of the gap size h variation

Products of plastics are formed at higher than ambient temperatures, in addition the product temperature is changing during the technological process and is needed to evaluate the temperature effect to the resonant frequency drift. There is a need to control polypropylene product manufacturing process at the temperature of (40...60) °C. Fig. 10 shows the resonance frequency drift due to temperature effect.

For the formation of products from plastics uses various fillings, which changes the dielectric properties. Fillers for microwave incur additional losses, which reduce the resonance curve parameters and reduce the potential to measure the thickness of plastic in this way. Fig. 11 shows

CST MWS derived curves from which we can see of dielectric loss impact on resonance parameters of the antenna.

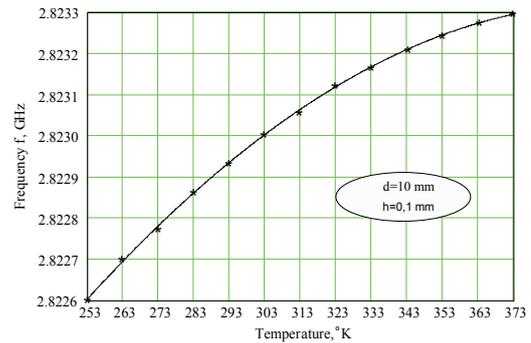


Fig. 10. Resonance frequency drift versus of the polypropylene slab temperature variation

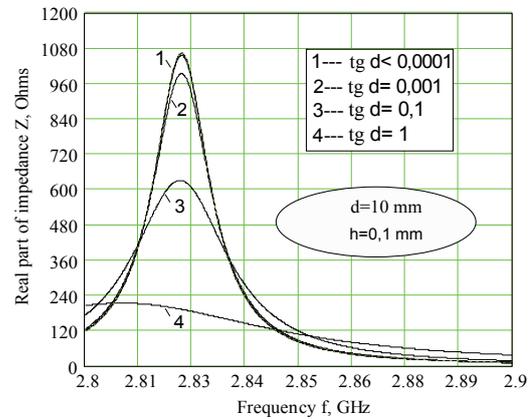


Fig. 11. The antenna impedance changes versus of the loss tangent

As shown in Fig. 11, the losses have a greater impact on $\tan \delta$ closer to 1. When $\tan \delta < 0,1$ (curves 3, 2, 1) loaded resonance quality Q varies in range from 235 to 980.

Phase detector circuit would achieve highest sensor sensitivity. For a constant frequency measurement, the phase shift as a function of the coupled with composite thickness permittivity change and can be approximated by [10]

$$\Delta\varphi = \frac{\pi}{2} \cdot Q \cdot \frac{\Delta\epsilon_r}{2}, \text{ when } \Delta\epsilon_r / \epsilon_r \ll 1, \quad (5)$$

where Q is the loaded resonance quality, and $\Delta\epsilon_r$ is absolute changes of the detected permittivity. A sensor phase sensitivity can be defined as

$$s = \frac{\Delta\varphi}{\Delta\epsilon_r} = \frac{\pi}{4} \cdot Q. \quad (6)$$

Sensitivity factor is in range 185 to 770, depending of loss. So the phase detector allows the design sensitive slab thickness sensors for high lossy composite if the absolute changes of the thickness (and permittivity also) are small.

Conclusions

A proximity-fed patch antenna sensor for evaluation

is used. The main element of the sensor is electromagnetic coupled patch – feed transmission line resonator, which allows to evaluate the thickness of the high loss composites via recording of resonant frequency or phase deviation. For sensing applications, due to high resonance quality (up to 1150 at 2,863 GHz), most suitable shunt (parallel) resonance of TLR. When composite $\tan \delta < 0,1$ and wall thickness is 10 mm, loaded resonance quality varies in range from 235 to 980. Phase detector circuit would achieve highest sensor sensitivity. Sensor phase sensitivity factor is in range from 185 to 770, depending of loss. Method is suited when the fixed air gap up to 1 mm between the wall and sensors occurs, and total loss tangent of dielectric is up to 0,1. With this method was evaluated polypropylene wall thickness measurement from 1 to 10 mm. Showed good spatial resolution, penetration depth and detection sensitivity.

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A proximity-fed electromagnetic coupled patch microwave sensor for evaluation of plastic wall thickness is presented in this article. Sensor is suitable to measure the thickness of the low permittivity and relative high total loss materials, when the opposite wall is not- or metal-backed and only one side of materials is an accessible. The main element of the sensor is electromagnetic coupled patch-feed transmission line resonator, which allows to evaluate the thickness of composites via recording of resonant frequency or phase deviation. It showed, that phase detector would achieve highest sensor sensitivity. Loaded resonance quality varies in range from 235 to 980 depending of measurement object loss. Sensor phase sensitivity factor range is from 185 to 770. Method is suited when the fixed air gap up to 1 mm between the wall and sensor occurs, and total loss tangent of dielectric is up to 0,1. With this method was evaluated polypropylene wall thickness measurement from 1 to 10 mm. Showed good spatial resolution, microwave penetration depth and detection sensitivity. Ill. 11, bibl. 10, tabl. 3 (in English; abstracts in English and Lithuanian).

A. Janeliauskas. Mikrobanginis plastiko sienelių storio matavimo jutiklis // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 7(123). – P. 69–74.

Nagrinėjamas artimuoju elektromagnetiniu lauku susietas mikrobanginis juostelinis plastiko storio matavimo jutiklis. Parodyta, kad jutiklis tinka mažos dielektrinės skvarbos ir palyginti didelių nuostolių medžiagų storiui matuoti, kai priešinga sienelės pusė yra laisva arba padengta metalu, o priėjimas yra tik iš vienos pusės. Pagrindinis jutiklio elementas yra elektromagnetiškai susietas juostelinių perdavimo linijų rezonatorius, kuris leidžia įvertinti kompozitų storį, stebint rezonansinio dažnio ar fazės pokyčius. Parodyta, kad naudojant fazės detektorių galima padidinti jautrumą. Apkrauto rezonatoriaus kokybė, priklausomai nuo nuostolių matuojamame objekte dydžio, kinta nuo 235 iki 980. Jutiklio fazės jautrumo faktorius yra nuo 185 iki 770. Matuoti galima, kai tarp sienelės ir jutiklio yra iki 1 mm pastovus oro tarpelis, o suminių nuostolių kampo tangentas neviršija 0,1. Pateikti polipropileno sienelės storio nuo 1 iki 10 mm matavimų modeliavimo rezultatai. Modeliavimo rezultatai parodė gerą skiriamumą, mikrobangų įsiskverbimo gylį ir matavimo jautrumą. Il. 11, bibl. 10, lent. 3 (anglų kalba; santraukos anglų ir lietuvių k.).