Open Stripline Resonator Sensor for Gauging in Industrial Applications

Nathan Ida [1] and Nader Farahat[2]

[1] Department of Electrical Engineering
The University of Akron, Akron, OH 44325-3904, USA
ida@uakron.edu.edu

[2] Department of Electrical and Computer Engineering
Polytechnic University of Puerto Rico, San Juan, PR 00919-2017, USA
nader.fatrahat@gmail.com

Abstract: A stripline resonator operating around 400 MHz was designed, analyzed and optimized for on line gauging of latex coated fabrics. The need for high accuracy, real time measurements and complete coverage of the fabric width necessitated a unique approach to the design including simulation and system development. The final production system consisted of a single sensor moving back and forth across the width of the fabric sampling the material continuously. A network analyzer proved to be a reasonable choice for the monitoring system because of its accuracy, ruggedness and because its interface allowed continuous modifications and analysis and monitoring across the internet so that engineers can remotely monitor the production, the quality of the product and intervene as needed. A computer monitors the motion of the sensor across the fabric, marks the location of the sensor and records the output together with time signatures and fabric data for later reference. Optimization of various parameters – size, sensitivity, interference and others was carried out using FDTD simulation. The results obtained from in-plant testing over many months proved to be excellent and repeatable under the most severe environmental conditions.

Keywords: Stripline resonator, microwave gauging, microwave sensor

1. Introduction

Moisture control in materials is essential for industries in production of food, paper, polymers and many others. In certain materials, such as rubber or latex-coated fabrics, the amount of coating material and the amount of water in the material are critical design parameters that influence the quality and ultimately the performance of these fabrics in the final product. These parameters must be tightly controlled both in terms of performance and cost. Too much absorbed solids (thick coatings) means considerable waste as well as degraded performance whereas too little coating means again degraded performance. The control of moisture affects both performance and quality of the product. In the production of coated fabrics (such as those used for production of tires), the fabric is dipped in a water solution of the coating material followed by removal of excess material (usually by blowing air across the fabric) and drying in an oven-like compartment in continuous production.

The normal process of controlling coating thickness is to sample the final product by cutting a section of the fabric and weighing it to determine the amount of material absorbed based on tables for each product. Should a sample prove to be inadequate the whole production run must be scrapped. This primitive method is also prone to errors due to moisture content. A poorly dried sample will indicate a heavy coating and vice versa.

In an attempt to improve the quality of the product and to reduce waste, a sensor and control system were designed based on open stripline resonators to accurately gauge the coating thickness. The requirements from the design were extremely limiting to begin with – an open system that would not interfere with the existing production line, on-line continuous monitoring, high accuracy and repeatability and almost absolute reliability were essential to gain approval from plant operators. Added to these were the environmental requirements of operating in a hostile environment rife with chemical vapors, almost 100% humidity, large temperature variations and possible contamination of the sensor with the coating material. We have, from the beginning, envisioned an autonomous system, separate from the production line that can be installed at various locations on the line, designed to test the whole width of the fabric continuously. To do so, the sensor was built so it can move across the fabric back and forth, to allow sufficient clearance for the fabric and to monitor the system in real time. To achieve all of these requirements we used a network analyzer and a computer system. The network analyzer, connected to the stripline sensors performed all the functions needed for monitoring of fabric conditions whereas the computer controlled the motion of the sensor across the fabric. Although a network analyzer is a sensitive and expensive piece of equipment, its accuracy, the fact that it can perform all the functions required (frequency scan, source power generation and analysis of the reflection signal) fully justified it use in this application. In addition, a single component system is valuable in maintenance – the network analyzer can be replaced in seconds and, if needed, serviced without interfering with production. The availability of a computer interface also allowed connection to the computer for data acquisition for archival purposes and monitoring of the operation over the internet to give engineers across the organization access to the data in almost real time.

In addition, the system can be, and will be used in the future to close the control loop by allowing the sensor system to control the drying and removal of excess material (through control of the speed of the fans) so as to keep the coating thickness constant. This is possible both because of the accuracy of the system and its quick response to relatively minor changes in coating thickness.

The strip-line resonator proved to be a reliable moisture sensor for online measurement of sheet-like products [1-3, 5]. As such, it has been used in the past for a number of applications including monitoring of paper thickness and drying [4], moisture monitoring in wood [6], and even in monitoring the drying of grain [7]. Nevertheless, the current system is unique in many ways. First, the two sections of the sensor are widely separated resulting in a reduced quality factor of the cavity but also more flexibility in the type of materials it can sense. Second, the sensitivity is much higher, primarily due to the use of the network analyzer but also from the design of the cavity and the motion system. Third, a complete analysis and simulation of the system has been carried out allowing for diverse influences including effects of moisture, temperature, contamination, proximity of personnel and many others as well as optimization of the sensor components themselves - stripline plates dimensions, shape spacing and location, coupling probes, shielding structure and others. In addition, the system incorporates automatic on-line calibration through use of reference sheets that bound the expected permittivity of the production material above and below, thus ensuring correct measurement of permittivity while removing uncertainties associated with environmental conditions.

2. Sensor Design

The design of the sensor system started with a double center-conductor stripline resonator shown in **Figure 1**. A resonator of this type is expected to have two modes: an odd mode (a) and an even mode (b) [7,8] The figure also shows possible coupling probes. This configuration is also known as broadside coupled stripline. The two resonant modes are defined by the capacitances of the empty cavity, the inductance and, of course, the permittivity of the measured fabric. The resonant frequencies of the cavities when the sample is present are given by:

$$f_o = \frac{1}{2\pi\sqrt{\mu_0 c_o/c_{o0}}}, \qquad f_e = \frac{1}{2\pi\sqrt{\mu_0 c_e/c_{e0}}} \tag{1}$$

where c_o and c_e are the capacitances for the odd and even mode and c_{o0} and c_{o0} are the capacitances for the even/odd modes when the cavity is empty [8]. In the sensor designed here these relations are only approximate since Eq. (1) assumes a uniform transmission line, whereas in our case the stripline only extends part of the length of the cavity.

As can be seen from Figure 1, in the even mode, the fields are parallel to the surface of the fabric whereas in the even mode they are perpendicular. Because of the fact that the fabric is thin and, hence the total perturbation volume in the cavity is small, the dielectric will influence the frequency of the odd mode very little – the shift in the odd resonant frequency due to the presence of the fabric is proportional to $(\varepsilon_r - 1)/\ \varepsilon_r$ with er the relative permittivity of the fabric (assuming the perturbation is small). In the even mode, with the electric field parallel to the dielectric, the shift in resonant frequency is proportional to $(\varepsilon_r - 1)$ [9]. Clearly the shift in resonant frequency of the even mode is much higher. Also, it should be noted that the odd and even mode frequencies are different with the even mode resonant frequency being lower. The use of the even mode frequency, although sensitive to both changes in permittivity (moisture content) and thickness of the dielectric, imposes some restrictions on the measurements. The most serious of these is the need to keep the sample at a fixed relative position with respect to the resonator plates, preferably at the exact center. In particular, vertical motion of the sample will result in errors in measurements. This restriction is not as serious with the odd mode since the fields around the center of the cavity tend to be more uniform. For this reason, the odd-mode resonant frequency has been suggested as a means of compensating for common-mode effects such as humidity and temperature [1, 5]

The two probes shown are used as a source and load probe for the network analyzer to monitor the S parameters. The excitation is through the gap between the probe and upper plate. To detect resonance only the S_{11} parameter is needed since at resonance the S_{11} parameter exhibits a sharp drop. Figure 2 shows a snapshot showing the even and odd resonant frequencies of the unloaded cavity in Figure 1 (without the bend-over shields) showing an even mode at 384.715 MHz and an odd mode at 428.243 Mhz as well as the FDTD simulated cavity showing the first even and odd modes as expected at 380 and 422 MHz respectively and a higher order (even) mode at 832 MHz.

To cover the entire width of the fabric there are two options: either create an array of sensors and multiplex their outputs to the network analyzer through switches or move a single sensor across the fabric. We opted for the second approach because microwave switches proved to be noisy and had a relatively short life span. In addition, the need to calibrate the sensor at given intervals allowed placement of the calibration sheets on either side of the fabric and simply extend the motion so that the sensor can sample the two calibration sheets. The motion of the sensor is affected either by two screw drives or a belt, moving the two halves of the sensor in tandem while controlling the position of the two halves relative to each other very tightly. The whole system is controlled through a computer which also schedules the calibration steps, acquires and stores the data and provides remote access through the internet or through lines.

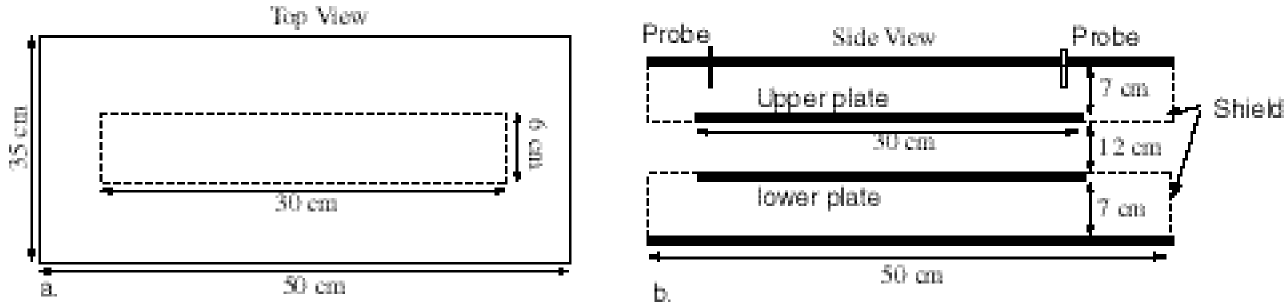
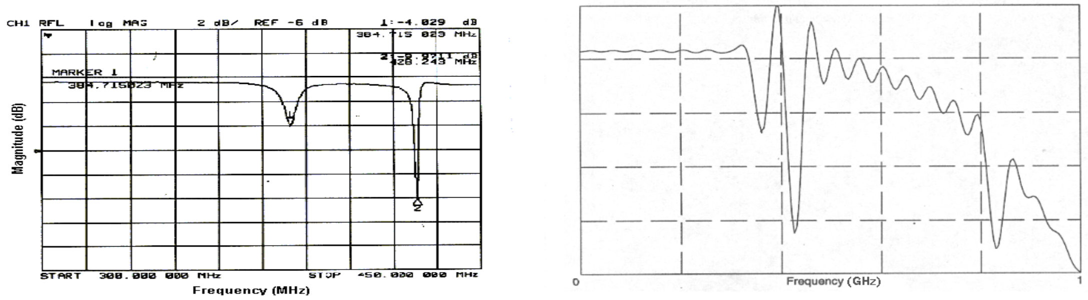


Figure 1. Structure and dimensions of the sensor. The shield is an open box, 7cm high with the plates making the stripline centered and flush with the openings of the shielding boxes which serve as the ground planes.

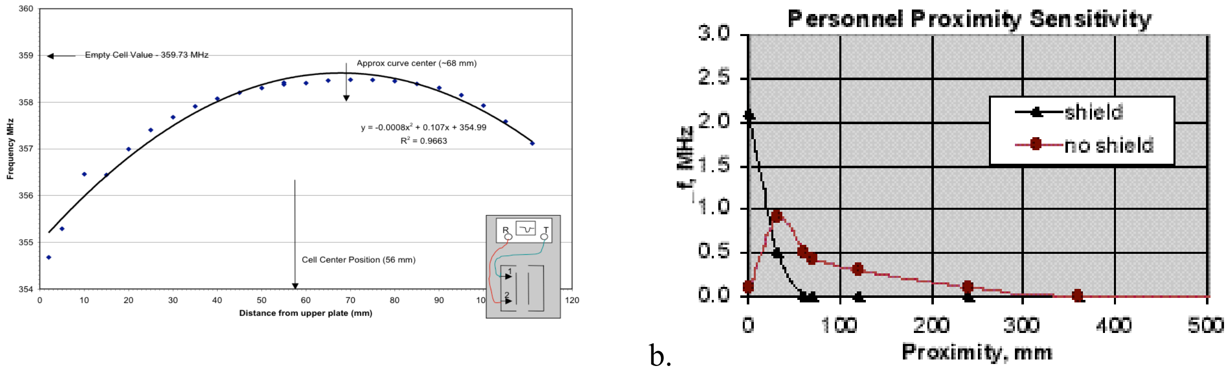


a. b.

Figure 2. A screen snapshot (left) showing the first even and odd resonant frequencies for the cavity in Figure 1 without the shield. b) FDTD simulation of the same cavity (right) showing the first even and odd modes and a second order even mode. Vertical scale is in db (relative).

3. Simulation and Measurements

The simulations were carried out using FDTD, first using a general purpose program followed by a commercial program. The purpose of simulations was to define the limiting parameters of the system including expected sensitivity, validation of dielectric mixture models and optimization of the various parameters including dimensions. An important role for the simulation was to evaluate the effects of external effects such as humidity, temperature and presence of personnel or machinery in the vicinity of the sensor. To demonstrate some of the results, consider Figure 3a which shows measured changes in resonant frequency due to position of the test sample within the gap between the two center plates in Figure 1. The center between the two plates is at 56 mm from the top plate (arrow). At the sample is moved above or below the center the resonant frequency goes down from about 358.7 MHz to less than 356 MHz when the sample is next to the upper plate. Figure 3b shows an FDTD simulation of the effect of proximity of personnel (modeled as a lossy dielectric block) with and without the shield. These changes are of the same order of magnitude as those due to variations in coating, clearly indicating the importance of keeping the fabric centered within the cavity. This is particularly important in widely separated plates as in our case (120 mm). These measurements were undertaken following simulations which showed that such variations might be an issue.



a. b.

Figure 3. a. Measurements of variations in the even mode resonant frequency due to location of the sample (Black Acetal Copolymer, 3.175 mm thick) relative to the center of the cavity. b. Simulation of effect of personnel proximity to the sensor with and without the shield.

A second important use of the simulation tool is the verification of the model for permittivity of the coating material and the fabric. Because the volume of the fabric is very small within the cavity, a simple mixture model was used to account for the expected effective permittivity of the composite sheet (made of the fabric and the coating material, which itself has many constituents, each with different permittivities). The fabric is of known composition (Nylon, Polyester) whereas the coating solution contains about 75-90% water, about 10% latex and smaller amounts of various solvents and other materials. To come up with a verifiable effective permittivity, the following model is used:

$$\varepsilon_{reff} = \frac{\sum_{i=1}^{n} \varepsilon_{ri} v_i}{\sum_{i=1}^{n} v_i} \tag{2}$$

This simple model proved to be accurate within the given data for permittivities of the constituents of the fabric and the solution and was used to decide on the calibration sheets. The latter were Nylon and Delrin, which are close in permittivity to the values predicted by Eq. (2).

The resonator in Figure 1 is the result of these optimizations. Whereas some parameters have little or no effect, some have profound effects. Other simulations looked at the effects of moisture on accuracy and repeatability of the results.

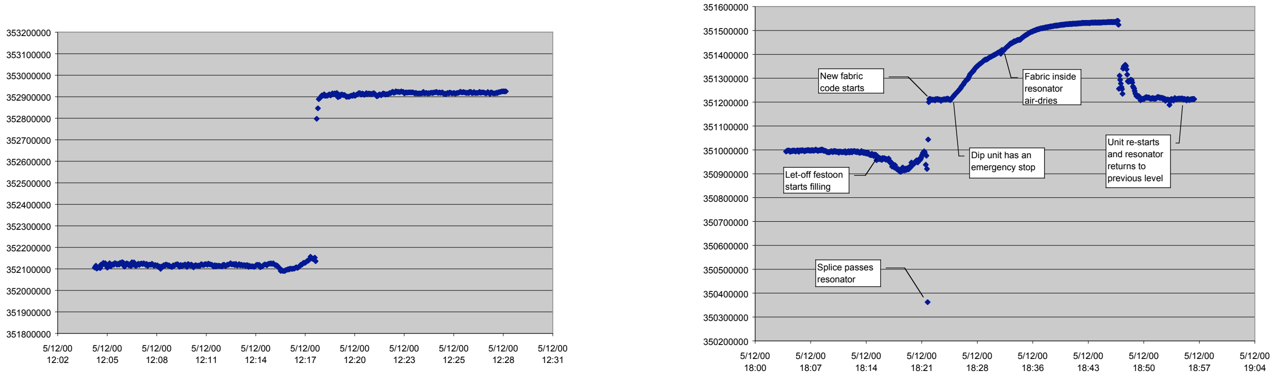
An important question in any sensor system is the expected sensitivity. In a system of the type given here, this is particularly important since that has to be defined ahead of prototyping and construction. This question was tackled in two ways. First, an analytical calculation was performed based on perturbation of an ideal cavity. The assumption was that a network analyzer can easily distinguish a 1 kHz change in resonant frequency. Most can do better than that. Nevertheless, our assumption for the final product was that the minimum distinguishing change in frequency is 10 kHz. A more useful approach is to use the simulation tool to define sensitivity. Table 1 shows such a calculation. In this, a 1mm fabric was assumed with relative permittivity of 2.5 which absorbs a given amount of the solution. The percentage of solids in the solution was 20%, the rest being water (relative permittivity 78). The amount of solution picked up by the fabric was between 30 and 40%. It is assumed that the rest of the volume (70% to 60%) is the fixed volume of the fabric. The effective permittivity in each case is calculated using Eq. (2) and the resonant frequency is then calculated using FDTD. Table 1 shows that a 5% change in solution pickup (thicker or thinner coating), which corresponds to 1% change in the amount of coating after drying results in a change in resonant frequency of 700 kHz. If we assume the network analyzer can reliably detect a 10 kHz shift in resonant frequency, then it can detect 1%*10kHz/700kHz = 0.014% change in solid coating pickup. Clearly this high sensitivity, which in fact can be even higher, is due primarily due to the high permittivity of water. What the system detects is the change in amount of water in the solution rather than the change in the amount of solids.

Table 1. Sensitivity to solid coating: solids. Solution: 20%, ($\varepsilon_r = 2.5$) water 80% ($\varepsilon_r = 78$), fabric ($\varepsilon_r = 2.5$)

% solution	ε_{eff}	Resonant frequency Even mode (MHz)	Resonant frequency Odd mode (MHz)
30%	20.62	374.4	424.3
35%	23.64	373.7	424.3
40%	26.66	373.0	424.3

4. On-Line Measurements

The system described above was built and tested in a plant for about 18 months prior to full scale production. Some typical results are shown in Figures 4. Figure 4a shows the resonant frequency for two different types of fabrics taken over a period of about half an hour. The one on the left moved faster and was more absorbent. The heavier coating results in a lower resonant frequency. The one on the right was less absorbent (less dense) and moved slower allowing the fans to remove more of the excess coating showing a change in resonant frequency of about 800 MHz. Figure 4b shows the output of the resonator during change of fabric with a different type. The plot shows the output over an hour and includes the splicing operation, emergency stoppage, drying of the fabric within the resonator while stopped and eventual re-starting and normal operation. Many other aspects of production can be detected, documented and corrected. These include streaking on the fabric, tears, folds, changes in line speed, changes in density of solution due to drying, contamination and others, all important from the quality control point of view.



a. b.

Figure 4. results from on-line gauging in the plant. b. Output from two different fabrics. b. Various conditions including splicing of fabrics, emergency stopping, drying out of fabric in the cavity and restart of motion.

5. Conclusions

The sensor and measurement system described here has proven to be more accurate than one would normally expect from an open microwave resonator leading to accurate gauging application to coated fabrics. The simulations carried out show excellent sensitivity and applicability to other types of applications with equal or better results. Although much of the sensitivity and accuracy can be attributed directly to the use of a network analyzer as a component in the system, this use is fully justified both from a cost-effectiveness point of view and from a maintenance point of view. The additional benefits of acquiring archival data, continuous on line calibration and correction, and remote accessibility allow for a flexibility not easily achieved with other systems. The methods developed here are directly applicable to a range of other industrial applications

References

[1] M. Fischer, “Microwave Stripline Sensors for Industrial Measurement Applications,” Thesis for the degree of Doctor of Technology, Helsinki University of Technology, Radio Laboratory, Report S 218, Nov. 1995.
[2] DuFore, S, “Sensor Development for the Control of Moisture Content in a Moving Fabric,” M.Sc. Thesis, The University of Akron, September 2000.
[3] A.J. Kraszewski, “Microwave aquametry – needs and perspectives,” IEEE Transactions on Microwave Theory and Techniques, Vol. 39, No. 5, pp. 828-835, May 1991.
[4] A.P. Kjaer, P.E. Westland and W.P. Heath, “On-Line sensing of paper machine wet-end properties: dry-line detector,” IEEE Transactions on Control Systems Technology, Vol. 5, No. 6, pp. 571-585, 1997.
[5] E. Nyfors and P. Vainikainen, “Industrial Microwave Sensors,” Artech House, Norwood, MA. 1989.
[6] R.J. King and J.C. Basuel, “measurement of basis weight and moisture content of composite boards using microwaves,” Forest Products Journal, Vol. 43, No. 9, pp. 15-22, 1993.
[7] R.J. King, K.V. King and K. Woo, “Microwave moisture measurement of grains,” IEEE Transactions on Instrumentation and Measurements, Vol. IM-41, No. 1, pp. 111-115, 1992.
[8] B. Bhat and S.K. Koul, “Stripline-Like Transmission Lines for Microwave Integrated Circuits,” John Wiley & Sons, New York, 1989.
[9] R. Harrington, “Time_Harmonic Electromagnetic Fields,” McGraw-Hill, NY, 1961.