Open Stripline Resonator Sensors for Rubber Properties Gauging

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Abstract — **Stripline resonators have been used in the past for detection and measurements, primarily in the paper and wood industries where they were used mainly for moisture control. The current work describes sensors and methods designed specifically for gauging – high accuracy measurements of dimensional as well as other parameters such as moisture content, mass and material composition, with specific application to rubber products and latex coated fabrics. Stripline resonators were designed, analyzed and optimized for production line gauging and monitoring of rubber thickness, for control of latex coating on latex coated nylon and polyester fabrics used in tire production and for moisture control in the curing of rubber products. 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. Sensor arrays as well as mechanically moving single sensors have been designed, built and tested in plants. The stripline resonators described here operate around 400 MHz – a frequency that allowed relatively simple structures with minimum interference from metallic and other conducting objects and yet allowed the physical size of the resonators to be small enough to account for local variations in material thickness and composition. A network analyzer is used to monitor the system's resonant frequency because of its accuracy, ruggedness and because its interface allows continuous modifications, analysis and monitoring across the internet so that engineers can remotely monitor the production, the quality of the product and intervene as needed. Although the cost of network analyzers is high, it forms a complete systems so that if it fails, it can be replaced in a few minutes, significantly reducing interruption in production. A computer monitors the motion of the sensor across the fabric or, in the case of arrays, the switching of the sensors, marks the location of the sensor and records the output together with time signatures and material data for later reference. Optimization of various parameters – size, sensitivity, interference and others was carried out using FDTD simulation. 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 sensors.**

I. INTRODUCTION

The term gauging usually refers to accurate measurements, most often, dimensional measurements. In the context of this work, it should be viewed in the broader context of accurate measurements of any parameter. In many cases, such as the case described here – that of measuring and controlling rubber sheets thickness – gauging is meant in the classical sense. In others, such as accurate sensing of amount of latex coating on fabrics, accurate control of moisture in a product or monitoring of solvents in polymers during curing or monitoring of material composition, the exact quantities are typically of no interest but the variations from a baseline value is more important. Nevertheless this is a gauging problem since the system is required to resolve down to values which are typically far below what is needed for normal control. The first problem addressed in this work is the coating of fabrics with latex. In this application the important parameters are moisture control and monitoring of amount of coating on the fabric. 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 (or solvent) 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 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. In production a continuous fabric, of widths up to 1.8m runs at various speeds often in excess of 10m/s. This requires the sensing system to respond quickly to prevent wastage and poor quality product.

The common 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.

A second important issue in production of solid rubber sheets of various thicknesses is accurate gauging of the thickness of the rubber during production. The purpose is to automatically adjust production parameters to guarantee a uniform up to specification sheet. Although there are other methods of gauging thickness (optical methods,

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electromagnetic transmission methods, nuclear absorption methods and others) these have been less than satisfactory for a variety of reasons. Optical methods tend to be spot methods whereas electromagnetic methods are not accurate enough, especially for thin materials. Nuclear methods are sufficiently accurate but they pose a number of problems associated with radiation safety and maintenance.

In both of the above types of materials, but in particular in latex-coated fabrics, material composition is also an issue. The amount of various constituents, especially the latex (but also solvents, wetting agents, etc.) must be controlled and tightly monitored since the amount of material in the final product (dry) is affected by the composition of the solution. It is therefore important to be able to monitor the composition either by the same sensor or by a separate sensor,

In an attempt to improve the quality of the products described above and to reduce waste, sensors and control systems were designed based on open stripline resonators to accurately gauge the coating thickness on fabrics and the thickness of rubber products. The two requirements are quite different as are the sensors designed for each. The basic requirements from the designs 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. In addition, there 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 sensors with the coating materials – rubber dust, latex splattering, and condensation.

We have, from the beginning, envisioned autonomous systems, 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, we first adopted a sensor array – a number of arrays staggered across the width of the fabric, operating in sequence. That is, each sensor was switched on by connecting it to a network analyzer to measure the resonant frequency from the S11 parameter. After measurement, the next sensor was switched on and this was repeated continuously. This intuitive method, while it worked well, required the use of microwave coaxial switches, which turned out to be less than perfect in reliability. A second generation sensing system abandoned the sensor array method in favor of a single sensor moving back and forth across the fabric. A number of critical issues including positioning accuracy and vibrations had to be resolved but overall the moving sensor systems were much more reliable than the switched sensors systems.

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 or rubber thickness 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 off-line 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.

The strip-line resonator has been proven to be a reliable moisture sensor for online measurement of sheet-like products in a number of previous applications [1-3, 5]. As such, it has been used in the past to monitor paper thickness and drying [4], moisture in wood [6], and even in monitoring the drying of grain [7]. Nevertheless, the systems described here are unique in many ways. First, the two sections of the sensor used for fabric monitoring 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 system used to measure rubber thickness, incorporates a curved cavity that uses a single microstrip plate operating against a conducting surface. To the best of the author's knowledge, this is the first time a sensor of this type has been described. Third, 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. Fourth, complete analysis and simulation of the sensors 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 structures and others. In addition, the sensor systems incorporate 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.

II. Sensor Design: Split Sensor for Fabric Monitoring

We started with the double center-conductor stripline resonator, also known as broadside coupled stripline shown in Fig. 1. A resonator of this type is expected to have two modes: an odd mode (a) and an even mode (b) [7,8] (see Fig. 2). Figure 1 also shows possible coupling probes. The two resonant modes are defined by the capacitances of the empty cavity, the inductance and, of course, the permittivity of the volume between the center plates. 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 odd and even mode capacitances per unit length and c_{o0} and c_{o0} are the even/odd modes capacitances per unit length 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.

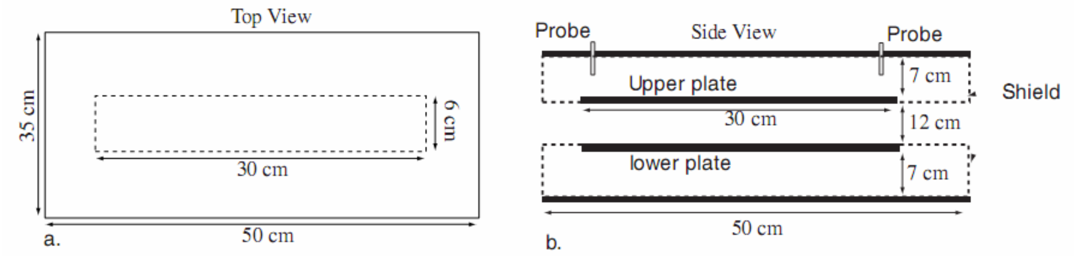


Fig. 1. Structure and dimensions of the sensor. The shield is an open box, 7cm high with the plates making the stripline centered and flush with the openings of the shielding boxes which serve as the ground planes. a. Top view, b. Side view.

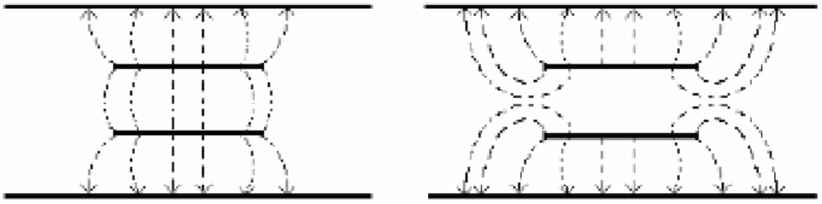


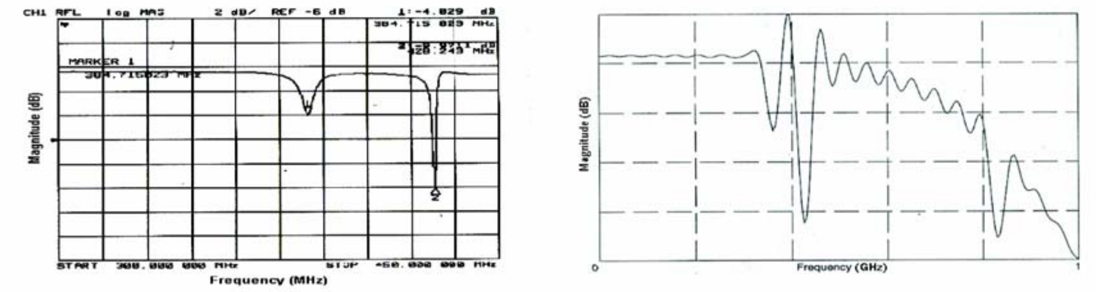
Fig. 2. Odd mode (left) and even mode (right) propagation in broadside coupled stripline.

In the even mode, the fields are parallel to the surface of the fabric whereas in the odd 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 ε_r 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]. The shift in resonant frequency of the even mode is much higher. To be noted is the fact 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 in Fig. 1 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 3a shows a screen snapshot showing the even and odd resonant frequencies of a simple cavity made as shown in Fig. 1 (but without 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. The same result is reproduced in Fig. 3b using an FDTD program.

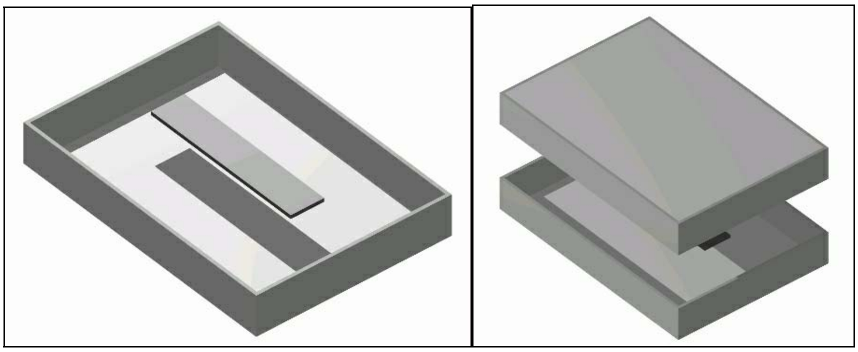
Following initial simulations, a shield has been added, resulting in a sensor made of two halves as shown in Fig. 4. The upper half contains the probes and the fabric moves midway between the two sections.

To cover the entire width of the fabric there are two options: One is the use of an array of sensors, staggered and switched to the network analyzer in sequence. The second option is to use a single sensor and move it back and forth across the fabric. Both of these options were explored. A configuration for the first option is shown in Fig. 5a. It consists of 9 sensors, staggered for complete coverage (a 10th sensor is used for calibration). The sensors are connected to the network analyzer through a sequence of switches as shown in the schematic in Fig. 5b. Although the system shown worked very well, the large number of switches (9 needed) turned out to be impractical. For a reasonable sampling rate (approximately one every two seconds), the switching rate was too high for the co-axial switches. The failure rate was much too high – approximately one switch every 2000 hours of continuous operation (3 months). At a cost of approximately $1000 a piece and taking into account the down time, the method was deemed impractical for industrial operation. In the first stage of modifications we removed the upper 6 sensors so that only 3 sensors plus the calibration sensors were left (lower row of sensors in Fig, 5a). This reduced the number of switches to two but also meant that sampling of the fabric was spotty. In particular, the edges of the fabric, where most problems with nonuniform covering occur were not sampled.



a. b.

Fig. 3. 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).



a. b.

Fig. 4. Representation of the cavity resonator. a. One half the cavity showing the position of the center conductor. b. The two halves opposing each other in the final sensor. Probes not shown.

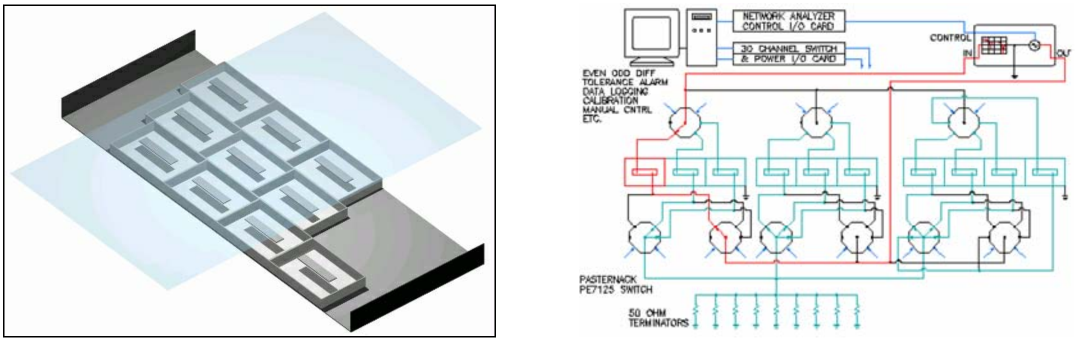


Fig. 5. a. The sensor array showing the 9 measuring sensor and the 10th, calibration sensor. The fabric and a support frame, which also serves as a second shield are also shown. b. Schematic showing the coaxial switches needed to operate the snsors in Fig. 5a.

The second approach explored was that of a single sensor, moving mechanically back and forth across the fabric. This is a counterintuitive approach as the motion must be exact and the two halves of the sensor must be rigidly positioned. Any vibration or misalignment leads to errors. Nevertheless, it was felt that once the mechanical system was in place, this would be a more reliable system. The final design relied on a heavy gage steel base and two screw drives driven by DC motors in tandem – a system that achieved a maximum misalignment of less than 0.1mm and negligible vibrations at the sensor. The need to calibrate the sensor at given intervals was solved by placement of two calibration sheets on either side of the fabric and simply extending the motion so that the sensor can sample the two calibration sheets. Th two calibration sheets are Nylon and Delrin since they bound the permittivity of the fabric below and above. 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.

III. SENSOR DESIGN: SINGLE SIDED SENSOR FOR RUBBER THICKNESS MEASUREMENTS

In the production of rubber sheets, the rubber passes over a cylindrical drum called calendar which both maintains its thickness and keeps it flat. For this purpose it was deemed essential that the rubber thickness be measured while the rubber sheet moves across the calendar. To do so, the sensor of Fig. 1 was modified in two ways. First, only the upper section was used complete with the two probes. Second, the sensor was made conformal by changing the plates and the shield to curved structure so that the distance between calendar and sensor components is constant. The sensor is shown schematically in Fig. 6. It is quite different than the structure in Fig. 1 but, as can be verified through application of image theory, the fields of the two structures are very similar, the main differences being introduced by the curvature of the structure in Fig. 6. In addition, the introduction of the conducting surfaces is expected to change the modes since the even mode fields, which are expected to be parallel to the surface were expected to be suppressed by this configuration. The odd mode on the other hand should change very little. This would basically imply that this sensor should be less sensitive than the sensor in Fig. 1 because of the expected suppression of the even mode. In practice, very little loss in sensitivity was observed in simulations as the results will show because the rubber is relatively thick (2-3 mm typically). The basic dimensions were left the same. The sensor is 50 cm long, 30 cm wide and 7 cm thick (the sensor in Fig. 6 is shown in cross section across its width – the second probe is behind the one shown). To optimize the sensitivity of the new sensor, the first adjustment was to make the geometry itself conformal by bending all conductors so that the distance between conductors and calendar is the same everywhere. This change further changes the resonant frequencies but also allows for more uniform coverage of the dielectric surface.

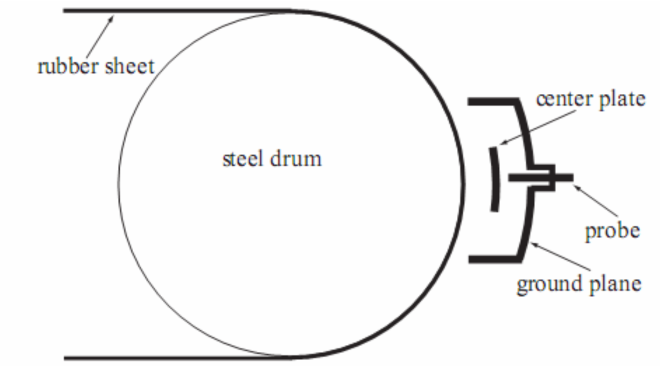
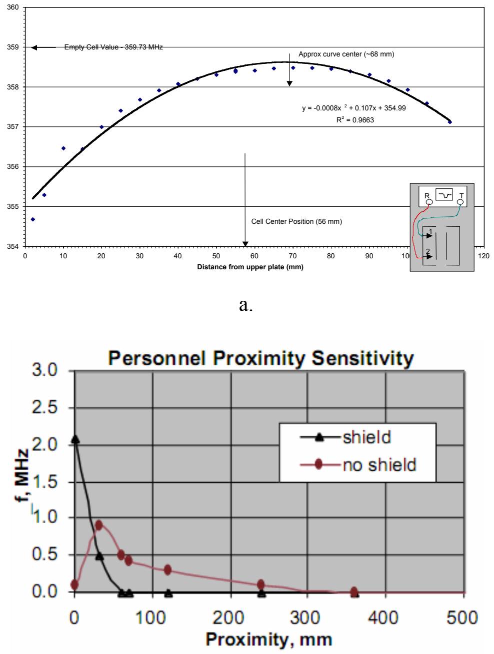


Fig. 6. Configuration used to measure rubber thickness with the rubber against a conducting steel drum (calendar). The probe is shown sideways from its narrow dimension.

IV. 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 limits 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. Simulations also looked at sensitivity changes due to separation between the two halves or between the sensor and calendar as well as dimensions of the center plate, shape of the plate, length and position of the probes and many others. A relatively low resonant frequency around 400 MHz was used based on previous experience with this type of resonators, a frequency dominated primarily by the dimensions of the cavity [10]. To demonstrate some of the results, consider Fig. 7a which shows measured changes in resonant frequency due to position of the test sample within the gap between the two center plates in Fig. 1. The center between the two plates is at 56 mm from the top plate (arrow). As 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. Fig. 7b 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 7. 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:

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

This simple mixing 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).

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 I. Sensitivity to solid coating: Solution: 20%, (ε_r = 2.5) water 80% (ε_r =78), fabric (ε_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

In the curved sensor in Fig. 2, likewise, the important optimization parameters were the distance between calendar and sensor, dimensions of the center plate as well as shape of the center plate. These were also simulated using the same FDTD tools.

The most important issue in the design was the sensitivity of the sensor to rubber thickness. Fig. 8 shows the sensitivity to rubber thickness at various sensor spacings between the sensor at the steel drum. Clearly, the larger the spacing the lower the sensitivity. Because of various constraints imposed by the need to access the drum surface a minimum distance of 3.5cm was deemed acceptable. To understand what kind of accuracy can be obtained, it is best to look at Table 2 which shows the actual calculated resonant frequencies at a separation of 3.5 cm. The table shows a shift in resonant frequency of approximately 1 MHz per mm rubber thickness. Considering the fact that even the simplest network analyzers can resolve down to less than 1 kHz, one can expect a basic measurement sensitivity of less than 1 micrometer. This computed sensitivity has been proven in experiments with a prior system [10]. As expected, at higher frequencies, the sensitivity should be higher. This is shown in the third column in Table 2 which shows the sensor sensitivity for the second resonant frequency (around 820 MHz).

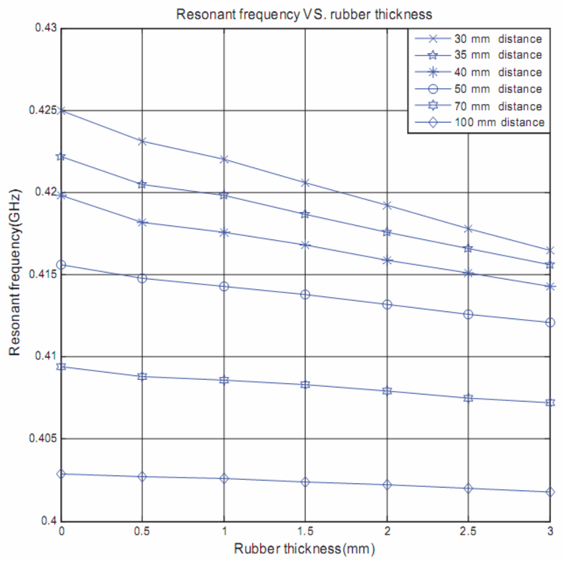


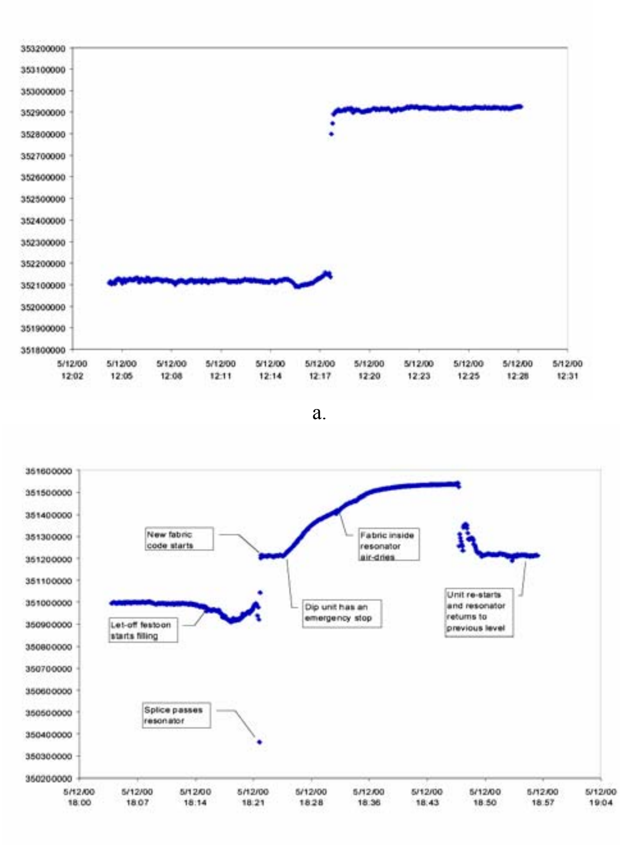
Fig. 8. Sensitivity to rubber thickness for various spacings between sensor and calendar in Fig. 2.

TABLE II. Resonant frequency versus rubber thickness at a sensor-calendar spacing of 3.5 cm

Thickness (mm)	1st Resonant Frequency (GHz)	2nd Resonant Frequency (GHz)
0.00	0.4222	0.8296
0.05	0.4205	0.8263
1.00	0.4198	0.8248
1.50	0.4187	0.8226
2.00	0.4176	0.8204
2.50	0.4166	0.8182
3.00	0.4156	0.8160

V. ON-LINE MEASUREMENTS

The fabric coating 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 Fig. 9. Fig. 9a 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. Fig. 9b 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.

Fig. 9. 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.

VI. CONCLUSIONS

Two types of open stripline resonant sensors have been designed and optimized for the purpose of gauging latex coated fabrics and for rubber thickness during production. The simulations carried out have shown a basic sensitivity down to less than 0.015% of solid coating and down to less than 1 micrometer for rubber thickness gauging. The sensors are part of a measurement system that includes sensor position control using a computer and resonant frequency measurement using a network analyzer. Simulation, optimization and analysis of the various parameters have been reported. The work reported here has shown that the main influence on sensitivity is that of the sensor's position but other components of the system influence sensitivity. Experiments as well as simulations have confirmed the basic conclusions of this work. 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.

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