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DUAL-MODE STRIPLINE RESONATOR ARRAY FOR FAST ERROR COMPENSATED MOISTURE MAPPING OF PAPER WEB

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ABSTRACT

A mechanically simple and therefore inexpensive sensor array for fast mapping of the water content of wet paper has been developed. The sensors are UHF strip-line resonators, which have two degenerate resonance modes, even and odd. By using the difference of these two frequencies a high accuracy can be achieved, because the resonance frequency of the odd mode is not affected by moisture changes in the wet paper, and can therefore be used for error compensation. Because of the electronic scanning the measurement is very fast and it makes almost real-time water content profiling possible.

INTRODUCTION

In the paper machine the moisture content of the paper web is a very important parameter of the machine control. Besides the data on the average moisture content also the spatial distribution of the moisture has to be measured in different parts of the machine. The transverse moisture profile is usually measured with a single mechanically scanning radio-active, infra-red or microwave moisture gauge. The measurement of one profile takes typically one minute and so the longitudinal sample spacing is several hundred meters. However, for the fastest controls and for diagnostic purposes, a faster mapping system is needed. This paper describes a realization of such an array with double center conductor stripline resonators to the "wet end" of the machine (after the press section), where 50-60 % of the total weight of the paper web is water. Due to the poor strentgh of the wet paper, the sensor has to be non-contacting. The ϵ_r' of the paper with this moisture content is about 30 and the thickness of the web is 0.03-1 mm.

THE DUAL-MODE SENSOR ARRAY

In the array each sensor is an open-ended half-wavelength strip-line resonator with two center conductors and two ground planes (Fig. 1). The length of the center strips directed along the web movement direction is 31.5 cm, width 4 cm and the vertical distance between the strips 5 cm. According to the laboratory tests, the sensors can be placed as close as 10 cm from each other (strip center to center). This is gained by using a unique *pin* diode switching technique to switch on the resonance of each sensor while the other sensors of the array are in non-resonant condition [1]. The both resonance frequencies of the sensors are measured in about 20 ms per sensor (see below). Thus the measurement time for a 5 m web is about one second (50 sensors), which is typically more than 50 times faster than with a single mechanically scanned sensor. Because of the simple structure of the sensors and the common measurement electronics, the array is fairly low-cost.

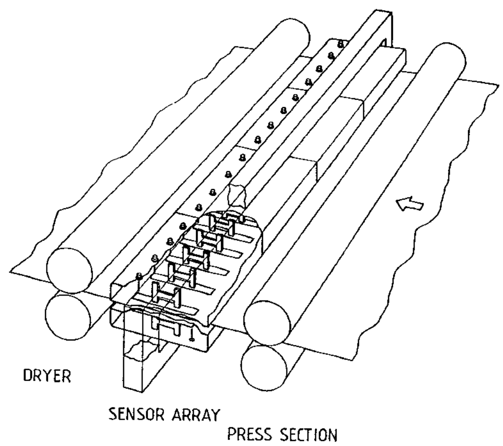

Figure 1. The resonator sensor array for on-line measurement of the water mass per area of paper.

The structure supports two degenerate quasi-TEM resonance modes, even and odd (Fig. 2) at about 400 MHz. Due to different end capacitances, the resonance frequencies f_{even} and f_{odd} of the modes differ with about 10 %. The Q factors of the resonances have been improved by bending down the edges of the ground planes. The electrical lenght of the strips is about 40 cm for the even mode and about 37 cm for the odd mode. The relative resonance frequency changes caused by the paper can be calculated using the following equation:

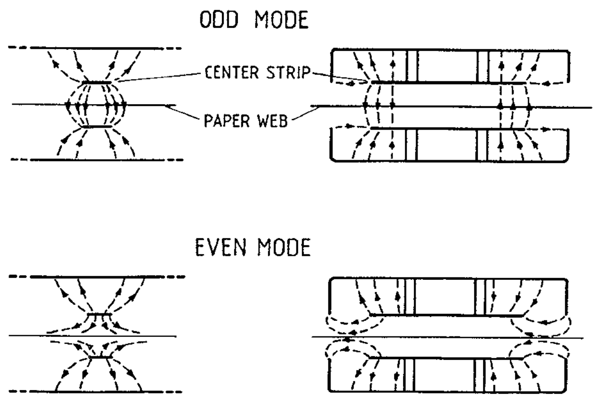

Figure 2. The cross section of the dual-mode stripline sensor with the electric field pattern shown for the even and odd resonance modes.

$$\frac{\Delta f}{f_o} \approx - \frac{\int_{V_p} \epsilon_o(\epsilon_r - 1)\bar{E}_p \cdot \bar{E}_o^* dV_p}{2\int_{V_t} \epsilon |\bar{E}_o|^2 dV_t} \approx$$

$$- \frac{(\epsilon_r - 1)d}{2} \cdot \frac{\int_{S_p} |\bar{E}_o|^2 (\sin^2\theta + \frac{\cos^2\theta}{\epsilon_r}) dS_p}{\int_{V_t} |\bar{E}_o|^2 dV_t}$$

In the equation $\Delta f / f_o$ is the relative frequency change, V_t is the volume of the sensor, ϵ_r is the dielectric constant of paper, E_o is the electric field strenght in air, E_p is the electric field strenght in paper, S_p is the area of the paper in the electric field of the resonator, d is the thickness of the paper and θ is the incident angle of the electric field strenght ($\theta = 0$ for normal incidence).

The left side of the equation is derived from the perturbation theory [2,3]. The right side as a function of the angle we get from the continuity of the tangential components of the electric fields and the normal components of the electric displacement at the air-paper boundary.

Angle θ depends on the location in the resonator. The volume integral can be replaced by the surface integral (right side of the equation) because the field strenght in the paper can be considered constant in the perpendicular direction because the paper is very thin. In the right side of the equation the ratio of the integral terms can be called a filling factor.

When the paper is placed in the middle between the center strips, the electric field of the even mode is parallel to the paper and the frequency shift is proportional to (ϵ_r' - 1). The electric field of the odd mode is perpendicular to the paper and the frequency shift is proportional to (ϵ_r' - 1)/ϵ_r'. Frequency changes as a function of the dielectric constant were measured for both modes (Fig. 3). The frequency change of the even mode is almost directly proportional to dielectric constant, but the frequency change of the odd mode is quickly saturated when the dielectric constant becomes large. When the dielectric constant is small, the frequency changes are the same for both modes. That is because the filling factor for the odd mode is about three times larger than the filling factor for the even mode.

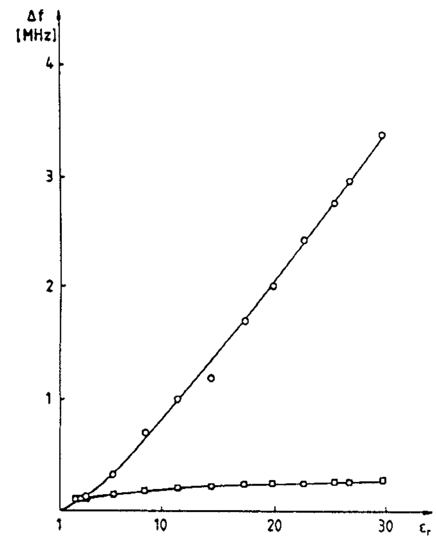

Figure 3. Changes in resonance frequencies as a function of the dielectric constant (o) even mode, (⊓) odd mode. Measurements have been made with paper and different plastics. Frequency changes correspond to 0.1 mm thick layers.

The relative dielectric constant of paper (ϵ_r) depends linearily on the moisture content (dry basis) and is between 25 and 40 after the press section of a paper machine. Due to the high ϵ_r', the change of Δf is much slower for the odd mode than for the even mode as ϵ_r' (i.e. the moisture content) changes. In this situation, the difference between f_{even} and f_{odd} depends on the moisture content of the paper. However, many causes of error have almost similar effect on both f_{even} and f_{odd}. Thus by using this difference the errors can be partly or almost completely compensated. The sensitivity of the difference of the resonance modes for the paper water content per unit area is about 25 kHz/(g/m^2). The required water content measurement accuracy after the press section is about 2 g/m^2.

ERROR COMPENSATION

For error compensation the resonance frequencies of both resonance modes are measured and their difference is used to detect the moisture content. Several disadvantages of the sensor are then compensated.

The dielectric constant of air is affected by humidity and temperature. The maximum effect on the resonance frequency of the one mode is about 100 kHz. However, the effect of the changes is similar for both resonance modes, if the filling factor for air in the whole resonator is the same for both modes, which is in practice the case.

With a large array slow changes in the dimensions of the array may occure due to temperature variations and gravity. The most severe effects are caused by the change in the vertical distance between the center conductors of the sensor. According to laboratory tests (Fig. 4) the effect of this change is about 300 kHz/mm to the even mode alone, but only about 50 kHz/mm to the frequency difference.

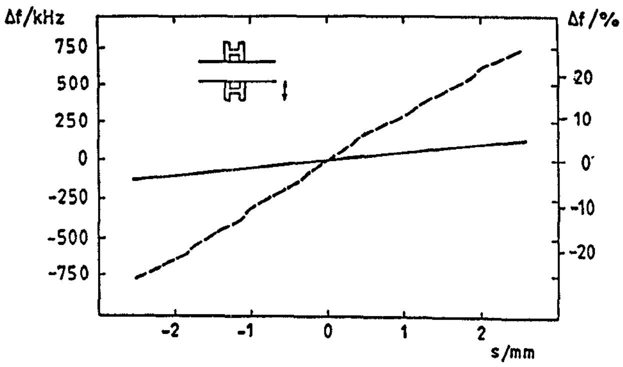

Figure 4. The effect of the change in the vertical distance between sensor strips. The dashed line shows the effect for the even mode alone and the solid line shows the effect for the difference of the resonance frequencies. The frequency shifts are presented in kHz and in percentages of the change that a wet 70 g/m^2 paper would cause.

The temperature of the array may change during measurement. The temperature coefficient of resonance frequency of the even mode is almost the same as the temperature expansion coefficient of the center conductors. When the frequency difference is used, the temperature dependence is about one third of the even mode temperature dependence.

The location of the paper in a sensor changes during measurement. The effect of this change is almost the same for the even mode as for the frequency difference and is about 0.25 % of the water content of the paper per one millimeter shift in the location of the web.

THE MEASUREMENT ELECTRONICS

One of the main advantages of this sensor array is its ability to perform almost real-time measurements. To accomplish this, fast resonance measurement system is needed. The sensors have to be measured in a succession because adjacent sensors disturb each other if they are resonating simultaneously. The fastest way to measure resonant frequency is to track the resonance peak with a lock-in type measurement system. With this method, response times of the order of 10 μs have been achieved [4]. With a sensor array, however, the measurement electronics has to be able to measure several dual-mode sensors having different resonant frequencies, quality factors and coupling coefficients. In this situation, a "fool-proof" surveillance-type measurement system was preferred. In theory it is possible to search the resonance peak with power measurement by examining the reflection or transmission response of the sensor. In practice, the reflection measurement is much more sensible to multiple reflections in the long cables between the measurement electronics and the resonator than the transmission measurement [5].

Due to the reasons above, a swept transmission response measurement system was used (see figure 5) . The system uses two switchable sweep ranges (width about 15 MHz) to measure both resonance modes. To gain adequate accuracy, frequency counting in the 3 dB points of the resonance peak is used to determine the resonance frequencies. The sensor being measured is connected to the measurement electronics with *pin* diode switches. The measurement time for one sensor (both resonance modes) is about 20 ms and the accuracy of the measurement of $f_{odd} - f_{even}$ is about 15 kHz.

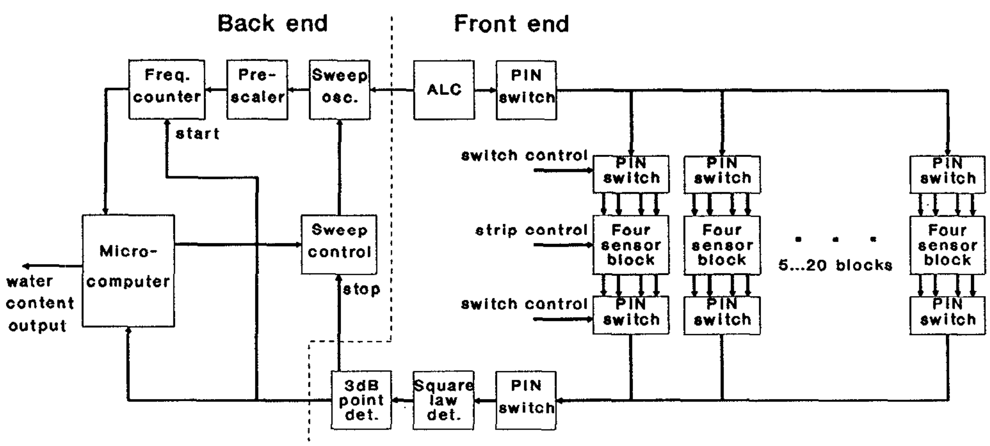

Figure 5. The block diagram of the measurement electronics of the sensor array.

CONCLUSIONS

A new apparatus for quick and accurate profiling of paper, board and cardboard has been developed. Because the array is mechanically simple and reliable and the operating frequency is about 400 MHz, the array is inexpensive. Due to electronic scanning, the measurement is very fast. Thus almost real-time water content profiling is possible.

Each sensor has two resonance modes and their frequencies differ by about 10 %. When the difference of these two resonance frequencies is used, several causes of error can be partly compensated. The effects of slow changes in the dimensions of the array, changes in the dielectric constant of air and the changes in the temperature of the array can be reduced.

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