A rugged active sensor for microwave aquametry

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***Abstract* — The paper introduces a compact active sensor of the resonant type for microwave aquametry. The proposed sensor is very simple yet accurate. The design procedure is described and experimental results are reported validating the sensor performance.**

I. INTRODUCTION

Microwave are specially suited to meet the growing demand in industrial processes for compact sensors with real-time monitoring capabilities, guarantying both compactness and performances, thus becoming more and more common in different area of the industry.

The sensor and the material under test (MUT) may interact in many forms but, in any case, the interaction between microwaves and matter is dominated by the complex dielectric permittivity of the medium.

Microwave aquametry represents the most important application for microwave sensors, as they exhibit an high sensitivity to water content in the MUT. Indeed, assuming that the real part of the permittivity of most dry material is lower than 10 while that of water is roughly 80, strong variation in dielectric permittivity are expected in presence of moistened materials.

The paper introduces a very compact microwave aquametry sensor of the resonant type, discussing the design issues for both the resonator and the active circuit. Measurements and experiment are reported and discussed to demonstrate the accuracy of the sensor.

II. BASIC STRUCTURE

Basically the sensor is a microwave open resonant cavity that interacts with the MUT. The interaction perturbs the cavity introducing a shift in the electrical characteristics of the resonator with respect to the unperturbed state. The shift of the resonant frequency introduced by the interaction is mainly due to the change in the real part of the dielectric permittivity. On the other hand, the losses determined by the imaginary part of ε lead to a quality factor decrease and a return / insertion loss increase.

The basic structure of the radiating head of the sensor is sketched in Fig.1. It consist on a planar ring resonator, excited by two microstrips, implemented on a second layer. The microstrips are electromagnetically coupled to the ring by means of two slots in the ground plane common to both layers, and terminated by short circuits in order to obtain a current maximum over the slots. The slots are positioned along a diameter of the resonant ring.

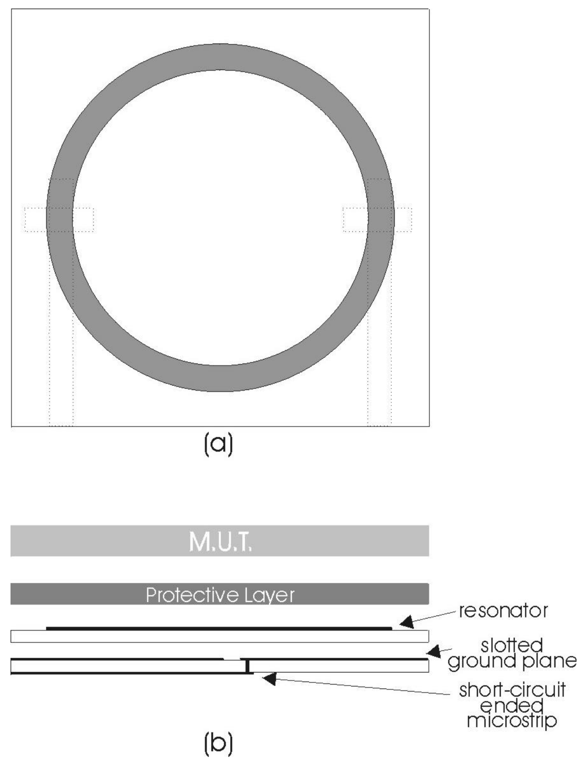

Fig.1. Plane view (a) and section (b) of the sensor.

The structure basically resembles a ring resonant antenna. As in the case of the antenna, the sensor uses the fringing of the electrical field on the microstrip ring, but, differently from the antenna case, an efficient radiation is undesired. In fact, an efficient radiation implies a deep penetration in the MUT that can represent a substantial drawback when thin layers and/or low permittivity materials are to be measured. A good choice is to tightly bound at the surface of the sensor the evanescent field with a suitable ring geometry and, most of all, with a proper feeding structure, as the one chosen.

The resonator can support several TM_{0m} modes in dependence of its electrical length and the resonance of the structure is, thus, bound to the TM mode excited over the ring. As previously discussed, the interaction with the MUT introduces changes in the resonator electrical characteristics. In particular a shift is expected in the resonant frequency. When the MUT has a low water content and a high degree of precision in the measure is desired, the sensitivity of the sensor must be high in order to ensure a good accuracy. This goal can be easily achieved by dimensioning the electrical length of the ring such as to support a high order TM mode, giving rise to a more sensitive frequency shift on these modes.

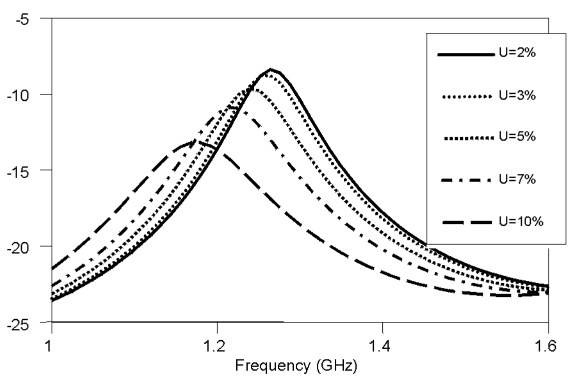

Fig.2. The sensor S_{21} variation for various water contents.

The proposed sensor is basically a two-port resonator. The scattering matrix, S, of the resonator in presence of the MUT contains the information regarding the moisture content. The transmission parameters ,Sij, are particularly useful, as they exhibit a considerable variation in center frequency, bandwidth and insertion loss due to the interaction with the MUT. Fig.2 reports the S_{21} variation for several water contents in the range 2- 10 %.

When the density of the materials in the compound is known or can be independently measured, as in the case of many industrial processes, the frequency shift induced by the water content is sufficient to extimate the water content in the MUT.

III. THE ACTIVE SENSOR

The frequency changes due to the interaction with the MUT can be directly measured arranging an oscillator around the sensor used as the frequency selective element. Stable operations for the oscillator calls for a fairly good quality factor of the sensor.

For the proposed structure, two basic oscillator topologies are possible. In the first, the sensor is configured as a two-port resonator connecting these two ports to the input and output ports of an amplifier; in the second, one port is used to furnish the frequency selective resonant element to a negative resistance oscillator, while the other port is loaded by a 50 Ω termination that represents the measure test point.

In principle, the phase shift oscillator guarantees more stable operations if compared to the negative resistance oscillator, as the loop phase shift is completely determined by the sensor and its corresponding variations due to the interaction with the MUT. However, two basic considerations discourage to use the phase shift oscillator. The first is that the frequency monitoring of the oscillator requires a carefully buffered loading, in order to avoid any pulling over oscillator frequency, due to parametric variations in the load during on-field operations. The second is that the sensor geometry requires the feeding along a diameter, as discussed earlier, and, thus, the feeding microstrips are fairly spaced. The insertion of the active elements implies the addition of transmission lines relatively long if compared to the operating wavelength that, correspondingly, will insert a substantial amount of phase variation along the oscillator loop, diminishing the resonator control over resonant frequency.

The design of a negative resistance oscillator is quite straightforward. The active element is connected to one port of the sensor, while the other port furnishes the measuring output. The implicit benefits of such an arrangement are that the output signal is filtered by the loop itself that, due to its loose coupling and its consequent fairly high insertion loss, prevents the load to pull the oscillator.

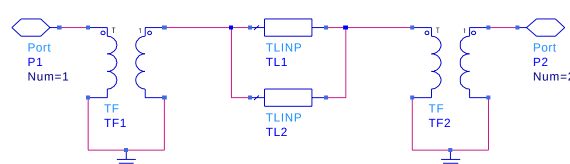

Fig.3. The lumped element model of the sensor on the fundamental mode

The main design guidelines for the oscillator are the thermal stability and the sensitivity to MUT parameters. The first issue is easily satisfied by properly biasing the active element, a general-purpose BJT in our case, with a fairly high emitter resistance. The collector is biased with a 5 mA current that gives a good compromise between phase noise performance and power consumption considerations.

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Table I - Equivalent line parameters

U (moisture content)	Eeff (equiv. perm.)	Loss (equiv. loss, dB/m)	Zo (line imp., O)
unloaded	1,963	0.614	50
2%	1.343	4.19	44.37
3%	2.351	4.55	44.29
5%	2.377	5.27	44.09
7%	2.409	6.44	43.84
10%	2.473	9.14	43.35

The oscillator was designed using an equivalent model, sketched in Fig.3, and dimensioned performing harmonic balance and time domain simulations to predict the frequency change due to a given variation in the moisture content. The model is arranged around two equal length physical transmission lines, whose parameters (i.e. equivalent permittivity, loss and characteristic impedance) are variable as a function of the moisture content of the MUT. The corresponding parameters, obtained with a least-square fit functional approximation by measured data, are reported in Table I.

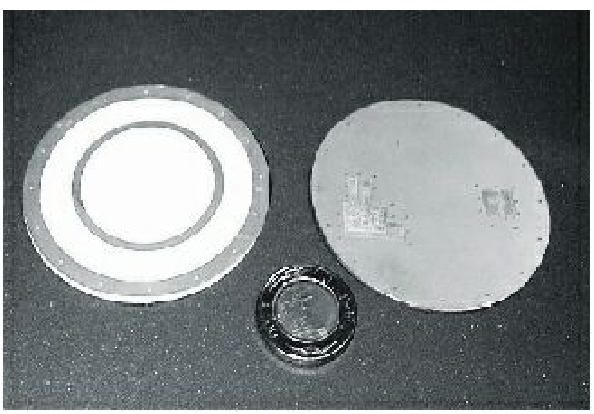

Fig.4. A photograph of the 1.4 GHz prototype.

Fig.4 reports a photograph of the sensor, realized on a Roacell RO03 substrate (ε_r=3.38, tgδ=0.002, tickness=31 mil, copper cladding = 1/2 oz/sq.foot). The dimension for the unloaded sensor operating frequency of about 1.4 GHz, using the fundamental mode of the resonator are: sensor outer diameter = 70 mm, medium diameter of the ring resonator = 41.5 mm, resonator line width = 3 mm .

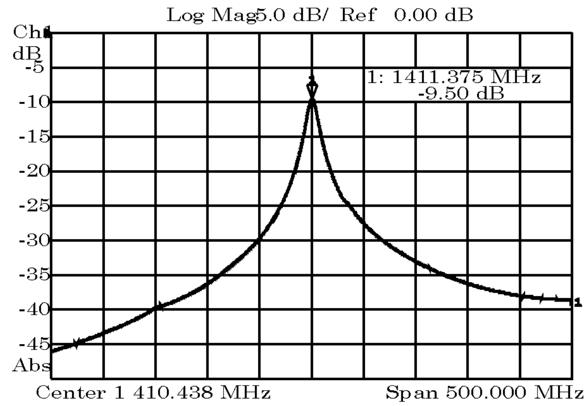

Fig.5 - S_{21} of the unloaded sensor

Fig.5 reports the transmission parameter, $|S_{21}|$, for the two-port unloaded sensor of Fig.4.

Fig.6 reports a comparison between active sensor output frequency and simulated sensor resonant frequency for various moisture contents, while Fig.7 reports the output

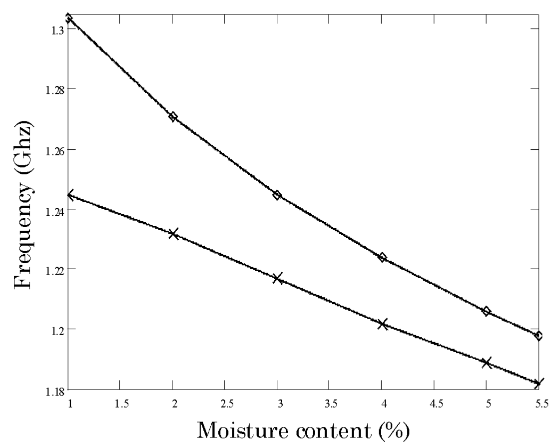

Fig.6. A comparison between the oscillator frequency (x) and the resonant frequency of the sensor (♦) for moisture content ranging from 1% to 5.5%.

spectrum of the unloaded sensor without the protective layer (radome).

It is worth to note that, as depicted in Fig.6, the oscillation frequency is not equal to the sensor resonating frequency , as the oscillation arises and is sustained at a frequency determined by both the sensor and active element reactive components. The diagram in Fig.6, in particular, evidences that the oscillator frequency varies roughly linearly, decreasing when the water content grows, while the resonant sensor frequency has a marked non-linear decrease.

The parametric variation due to the temperature are removed by constructing two equal active sensors, the one

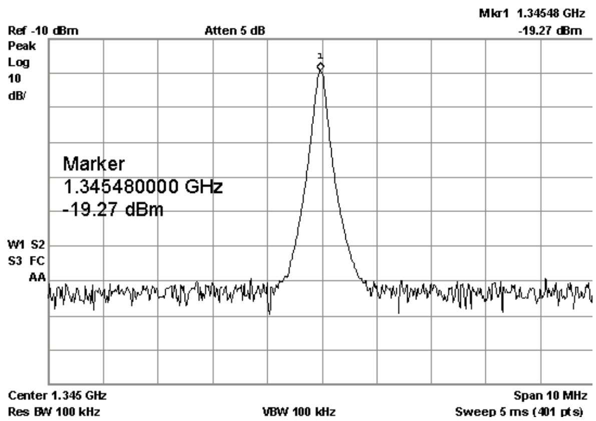

Fig.7. The output spectrum of the sensor .

interacting with the MUT and the latter loaded by a reference material and sealed in an suitable enclosure. The two signals feed a mixer whose output is the difference between the frequencies, used for the measure.

IV. Conclusion

The proposed sensor is extremely compact and guarantees a good sensitivity to water content variations in the MUT. Further work is in progress with the aim to extract density information from the measurement.

References

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