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Three techniques for characterizing materials using microwaves

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José Roberto Reyes Ayona[1]*, José Ramón Aviña Ortiz[1], Edgar Reyes Ayona[2], Roberto Rojas Laguna[1], Juan Manuel Sierra Hernandez[1]

1 *University of Guanajuato, Electronics Department, DICIS, Salamanca, México*

2 *National Polytechnic Institute, Interdisciplinary Professional Engineering Faculty, Guanajuato Campus, Silao, México*

UPIIG Unidad Profesional Interdisciplinaria de Ingenierías Campus Guanajuato IPN

SUMMARY

Microwave-based material characterization techniques that are non-invasive, reliable, and applicable to most solid, liquid, and gaseous materials are presented in this work. Depending on the characteristics of the materials, variations in the resonance frequency value, a specific behavior over a frequency range, or changes in resonance bandwidths may be utilized. These parameters can be used to assess material authenticity, quantify contamination levels, determine moisture content, characterize chemical composition, evaluate quality indicators, and classify materials.

CHANGES IN RESONANCE FREQUENCY

A microstrip resonator shown in Fig. 1 is used as a permittivity sensor by incorporating metamaterial design techniques, which make it highly sensitive and particularly effective for organic materials, which typically exhibit significant losses [1].

a) b)

Figure 1. (a) Top view and (b) front view of a rectangular resonator.

The sensor operates by detecting changes in its resonant frequency when a material is placed on its surface and correlating these changes with properties such as maturity, spoilage, authenticity, and moisture content of the sample [1–3]. Equation (1) shows the relationship between the resonant frequency, f_r , and the relative permittivity, ε_r, of the sample.

$$f_r = \frac{c}{\sqrt{\varepsilon_r}\, l_g} \qquad (1)$$

where c is the speed of light and l_g is the guided wavelength, which is determined by the geometry, dimensions, and type of sensor.

Figure 2 shows the frequency response of two sensors used to detect the moisture content of sliced potatoes, where substantial changes in the frequency values can be observed.

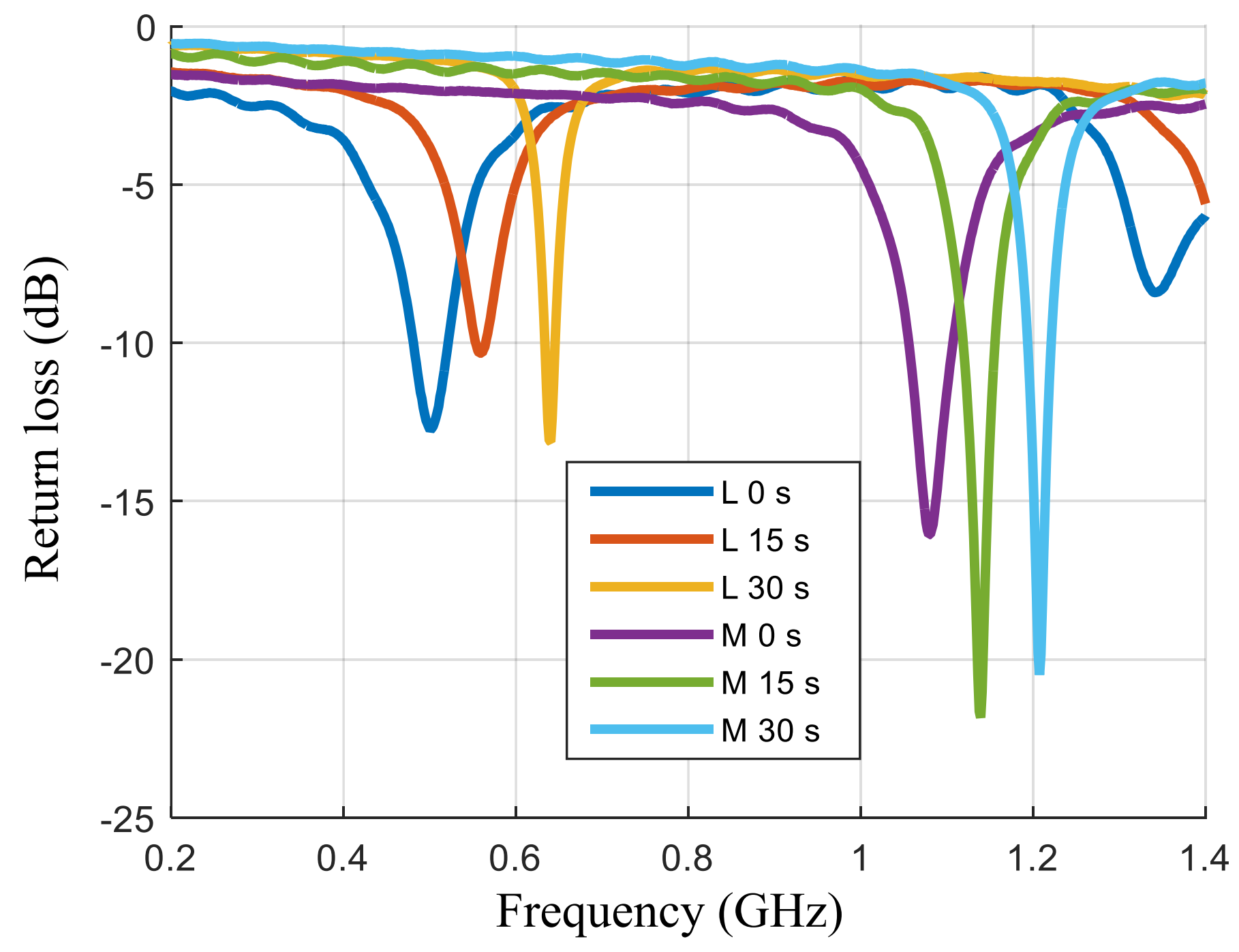


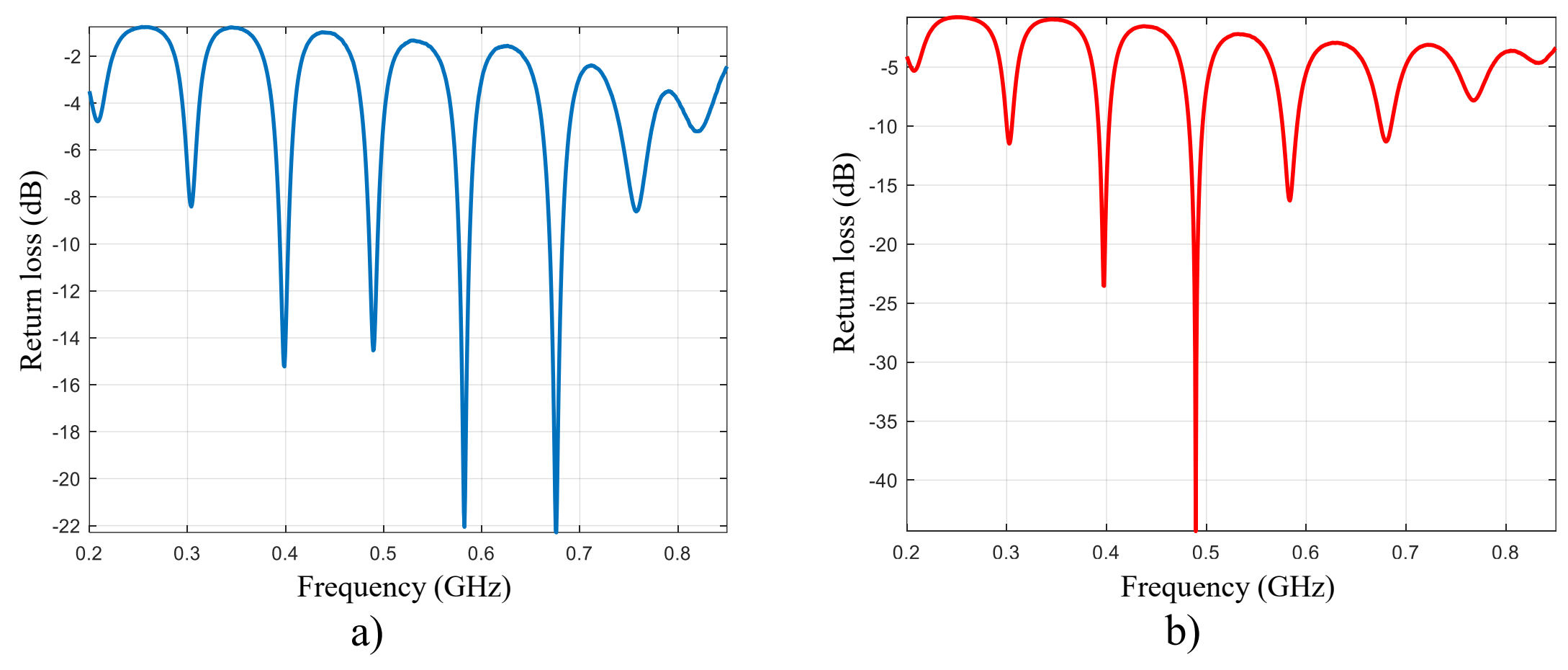
Figure 2. Response of sensors L and M for potato samples subjected to different exposure times (in seconds) to hot air during the drying process.

RESONANCE COMB

Another technique is based on analyzing the multiple resonances (frequency comb) that occur within a broad frequency region (operating bandwidth). The main difference from the first technique is that the emphasis is not placed on the exact value of the resonant frequency, but rather on the behavior of the resonances within a given frequency range.

If the samples have a very low relative permittivity, ε_r (such as gases), or if the objective is to detect variations in samples with a very high ε_r (such as contaminants in water), the resulting shifts in resonant frequency become practically imperceptible. For example, consider water with $\varepsilon_r = 80$ and the detection of a 0.1% increase in a contaminant such as bleach with $\varepsilon_r = 79.999$ within that volume of water. The corresponding refractive indices would be 8.944271 and 8.944216, respectively. In situations such as this, the changes in the resonant frequency value fall within the measurement uncertainty of the instrumentation and are therefore difficult to detect reliably.

However, with appropriate modifications to the permittivity sensor design and the detection system, it is still possible to identify changes in the samples. Figure 3 shows the frequency response of a sensor in the 200 MHz to 850 MHz range for water without salt (left curve, blue) and for water with 60 mL/L of salt (right curve, red). As can be observed, there are changes in the amplitudes of the resonances (but not in their frequencies), and Figure 4 shows these variations for water with 0 to 60 mL/L of salt across six different resonant frequencies.



a) b)

Figure 3. Sensor response as a function of frequency for water samples with (a) 0 mL/L of added salt, and (b) 59 mL/L of added salt.

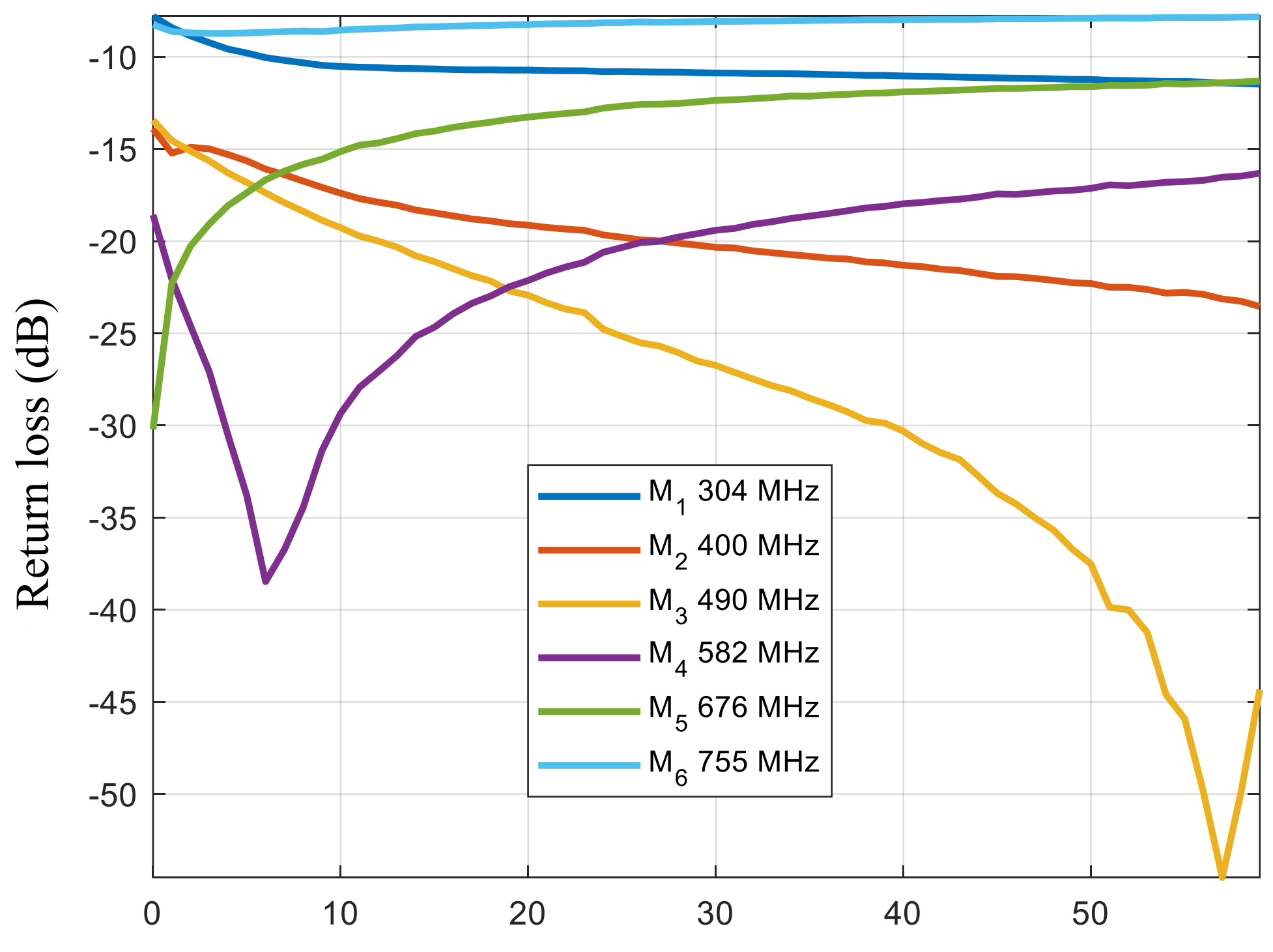


Figure 4. Return loss values as a function of the amount of salt added to the water for six different frequency ranges.

CHANGES IN RESONANCE WIDTHS

The resonance bandwidth is directly related to the quality factor Q. For two-port devices, it is given by

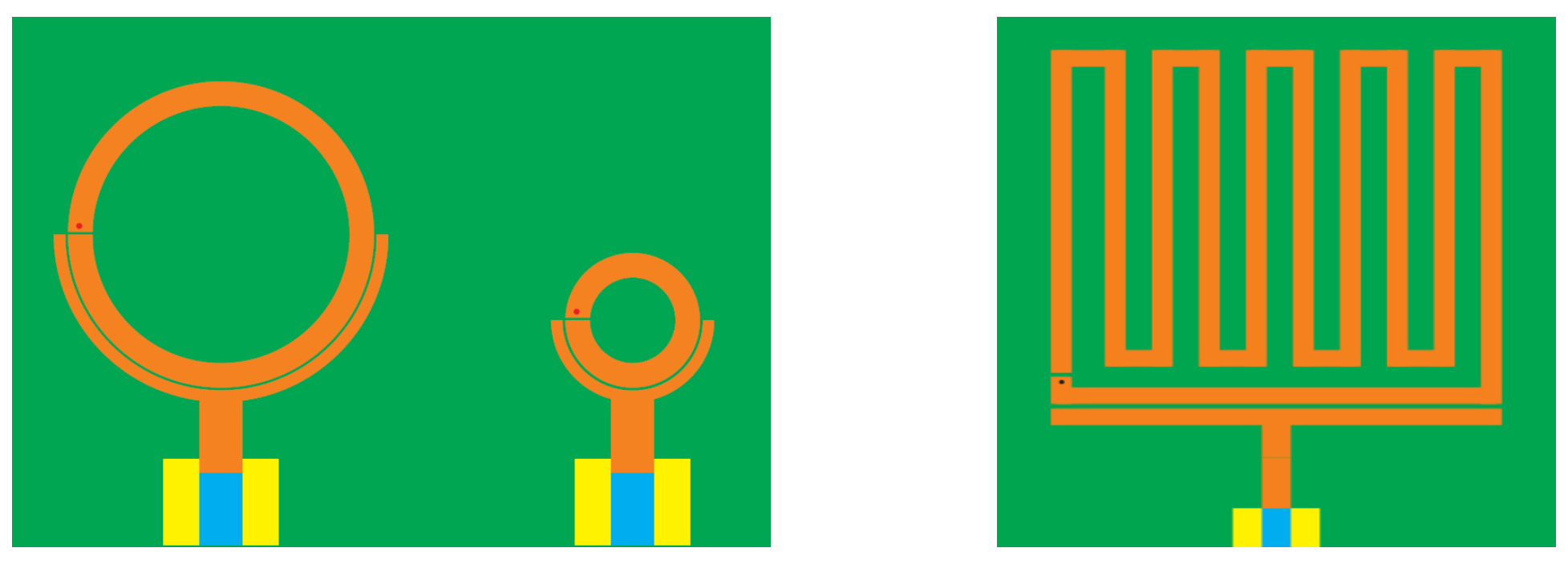
$$Q = \frac{f_r}{\Delta f_{3\mathrm{dB}}} \qquad (2)$$

where $\Delta f_{3\mathrm{dB}}$ is the resonant bandwidth at half-power (3 dB) level.

Q can be associated with the imaginary part of the permittivity and can be used to obtain chemical properties in materials.

RESONATORS´ CHARACTERISTICS

Another advantage of a resonator designed using metamaterial techniques is that it can be adapted to the size or type of sample being characterized. This not only allows operation across different frequency ranges but also makes it possible to focus on the center, perimeter, or entire volume of the sample, depending on the requirements. Figure 5 shows the schematic of a printed circuit board (PCB) for (a) two circular resonators of different sizes and (b) a fractal resonator. These are used in different applications with distinct characterization techniques.



a) b)

Figure 5. PCB schematic for (a) circular resonators designed with an emphasis on shifts in resonant frequency, and (b) a fractal resonator designed to generate a frequency comb.

CONCLUSION

Three different techniques were presented for characterizing solid, liquid, and gaseous materials in the microwave range using a permittivity sensor. These approaches allow the characterization of samples that exhibit large variations in permittivity, samples with almost no detectable changes in permittivity, or cases in which only the imaginary part of the permittivity changes significantly.

REFERENCES

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