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Portable Ring-Resonator Permittivity Measurement System: Design & Operation

by Gregory Mazzaro, Kelly Sherbondy, Gregory Smith, Marc Ressler, and Russell Harris

ARL-TR-5993 **April 2012**

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Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT
A method for measuring complex permittivity using ring resonators is presented. The measurement is suitable for ultra-wideband ground-penetrating radar frequencies. The ring-resonator technique is portable, wideband, and can be performed in-situ, without disturbing the dielectric sample. Design equations and physical dimensions are presented for fabricating traditional rings at frequencies between 600 MHz and 2 GHz. The meander-line ring-resonator concept extends the effective measurement frequency range below 600 MHz. The measurement procedure is explained, step-by-step. Only a handheld vector network analyzer, coaxial cabling, and the ring resonators are necessary for the measurement. A Matlab script, which references lookup curves generated in FEKO, calculates the complex permittivity. Values for the real and imaginary parts of the permittivity can be generated as each sample is measured, or they can be generated after all of the samples have been measured. Data is presented for samples of soils and homemade explosive simulants.

15. SUBJECT TERMS
Permittivity, dielectric, measurement, portable, ground-penetrating radar, ring resonator, soil, meander line

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1. Introduction

1.1 Relationship to Ground-Penetrating Radar

Proper development of ultra-wideband (UWB) ground-penetrating radar (GPR) technology requires a unique understanding of the electromagnetic (EM) properties of target and background deployments. Thus, EM characterization of targets and backgrounds is fundamental to the success or failure of UWB GPR as a threat detection technique.

In many cases, threats to the Soldier are buried in soil. Soil properties directly affect the radar signature of targets and determine the depth at which they can be detected. One such property is permittivity, ε. Permittivity indicates the transmission, reflection, and absorption of EM radiation by a dielectric material. It is an intrinsic material property that depends greatly on water content and to a lesser degree on temperature; therefore, ε for sand, soil, and vegetation varies by location and time-of-day. Thus, to accurately model the behavior of radar pulses in a test environment, permittivity must be measured as near to the radar test area as possible.

A portable system recently developed at the U.S. Army Research Laboratory (ARL) measures permittivity in-situ with minimal disturbance of the dielectric sample. The measurement technique uses ring resonators.

1.2 Traditional Ring Resonator Design and Properties

A ring resonator is a two-port transmission-line structure consisting of an input feedline, a closed loop, an output feedline, and two coupling gaps, as seen in figure 1.

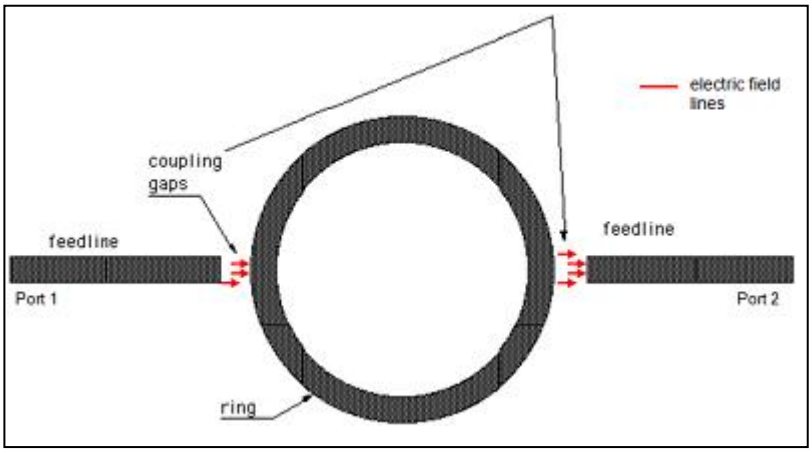

Figure 1. Traditional ring-resonator: top view.

The ring is the signal-carrying conductor of a microstrip configuration. Beneath the ring is a printed-circuit-board (PCB) dielectric of constant thickness and permittivity, and beneath the PCB dielectric is a metal ground plane (at least as wide as the ring, from feedline to feedline).

Radio-frequency (RF) energy couples into and out of the resonator via the feedlines and coupling gaps. Resonance is established when the wavelength of RF propagating in the transmission line (or an integral multiple thereof) equals the circumference of the ring (*1*),

$$2\pi r_{\text{avg}} = n\lambda_g \qquad r_{\text{avg}} = \frac{1}{2}\left(r_i + r_o\right) \tag{1}$$

where r_{avg} is the radius of the ring averaged between its inner radius r_{i} and outer radius, r_{o}, λ_{g} is the guided wavelength, and n is the mode number. The fundamental resonant frequency of the ring f_0, corresponding to $n = 1$, is equal to

$$f_0 = \frac{\nu}{\lambda_{\text{g}}} = \frac{c}{\lambda_{\text{g}}\sqrt{|\varepsilon_{\text{eff}}|}} \tag{2}$$

where c is the speed of light in a vacuum and ε_{eff} is the effective dielectric constant of the unloaded transmission-line structure. At this frequency, the two-port transmission coefficient $|S_{21}|$, measured from the input feedline to the output feedline, reaches a local maximum. Maxima are also observed at $n = 2, 3, 4...$, corresponding to integer multiples of the fundamental frequency ($2f_0$, $3f_0$, $4f_0$, etc.). Simulated transmission-coefficient maxima are observed in figure 2.

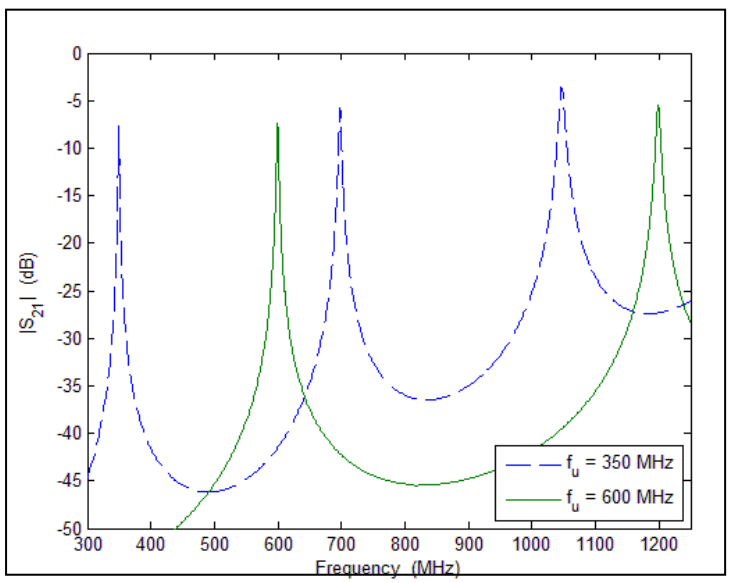

Figure 2. Transmission coefficient $|S_{21}|$ vs. frequency for two simulated ring resonators. The first 3 harmonics of a 350-MHz resonator and the first 2 harmonics of a 600-MHz resonator are shown.

1.3 Ring-Resonator Permittivity Measurement Concept

The change in the resonance of the ring measured in the presence of a dielectric sample and that measured in the absence of the dielectric sample enables the calculation of the sample's

permittivity (*2*). Figures 3, 4, and 5 illustrate the measurement concept. The example shown is for a 350-MHz meander-line ring resonator.

First, the resonator is left unloaded, with only air occupying the space above the ring, as in figure 3a. The transmission coefficient $|S_{21}|$ of the resonator in air is recorded using a network analyzer, as in figure 4. The frequency at the resonant peak, f_u, and the quality factor of the resonance, Q_u, are noted. Next, the dielectric sample is placed on top of the resonator (or vice versa), as in figure 3b. The ring and the sample are pressed together so that the two are flush. A second $|S_{21}|$ trace is recorded for the resonator loaded by the dielectric sample, as in figure 4. The new resonant frequency, f_l, and quality factor, Q_l, are noted. The shift in the peak of the resonance with respect to frequency indicates the real part of the permittivity, $Re\{\varepsilon\}$. The widening of the peak of the resonance indicates the imaginary part of the permittivity, $Im\{\varepsilon\}$.

Permittivity values are normally reported after they are normalized to the permittivity of free space:

$$\begin{aligned} \varepsilon &= \mathrm{Re}\{\varepsilon\} + j \cdot \mathrm{Im}\{\varepsilon\} \\ \varepsilon_r &= \frac{\mathrm{Re}\{\varepsilon\}}{\varepsilon_0} + j \cdot \frac{\mathrm{Im}\{\varepsilon\}}{\varepsilon_0} = \mathrm{Re}\{\varepsilon_r\} + j \cdot \mathrm{Im}\{\varepsilon_r\} \end{aligned}, \tag{3}$$

where $\varepsilon_0 = 8.85 \times 10^{-12}\,\mathrm{F/m}$. The quantities $Re\{\varepsilon_r\}$ and $Im\{\varepsilon_r\}$ are the real and imaginary parts of the relative permittivity, respectively.

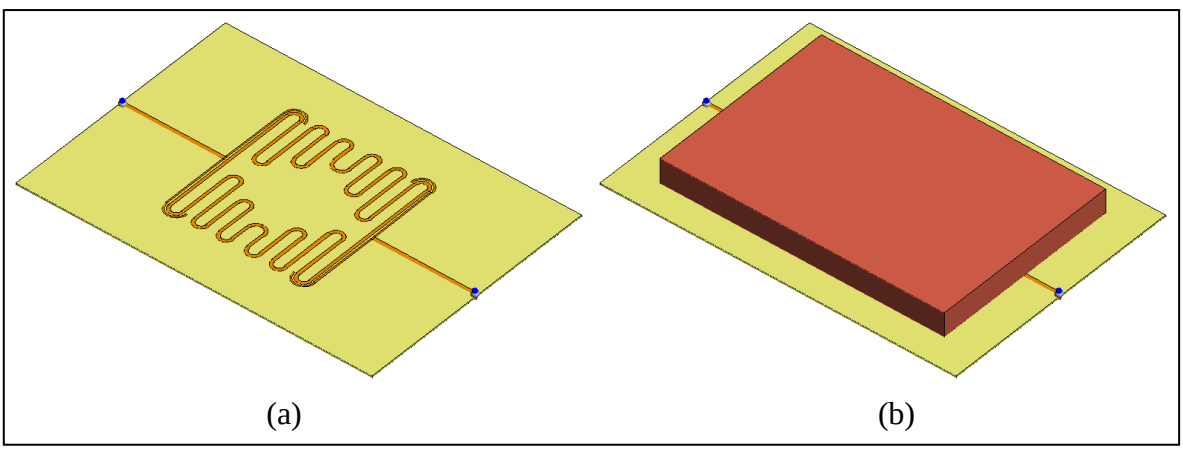

Figure 3. Ring resonator and sample placement required for permittivity measurement: (a) resonator left unloaded, (b) resonator loaded by dielectric sample.

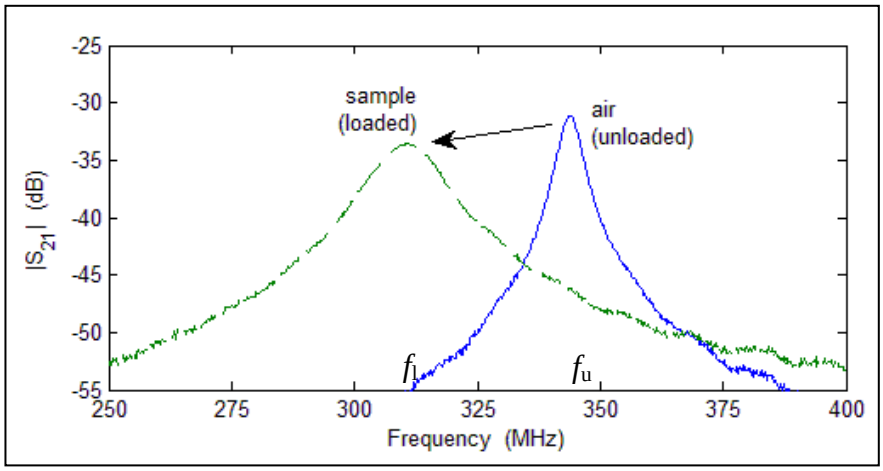

Figure 4. Data traces for permittivity measurement, before and after dielectric loading.

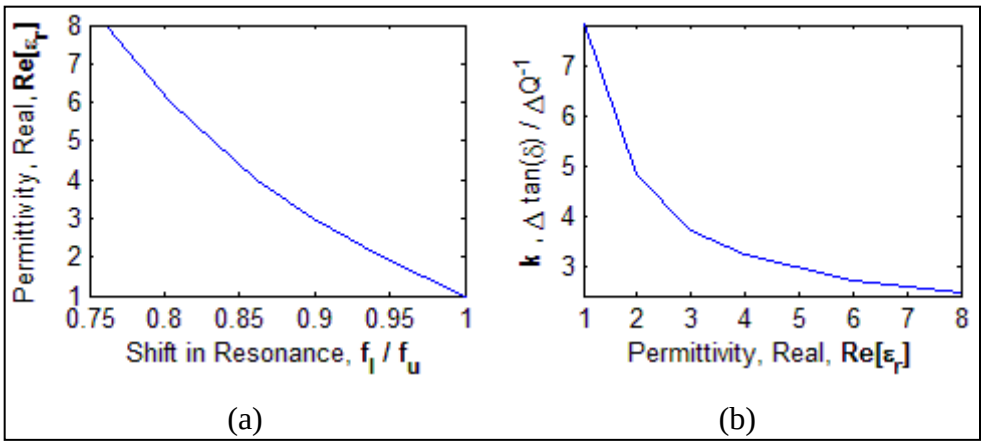

Figure 5. Curves used to determine permittivity of the sample, generated by simulation: (a) real part of ε_r, (b) k value used to calculate imaginary part of ε_r.

Each ring resonator (and each harmonic of its fundamental resonance) has a characteristic $Re\{\varepsilon_r\}$-vs.-resonant-frequency curve, as in figure 5a. These curves are generated by repeated simulation using the procedure of the preceding paragraph and samples with different dielectric constants. From the measured data, the ratio of the resonant peaks, f_l / f_u, is calculated. This ratio is the x-value of figure 5a. The real part of the permittivity is the corresponding y-value along this curve.

The imaginary part of the sample's permittivity is determined using figure 5b. Here, the real part of the permittivity is the x-value along the curve. The y-value is k, a constant that indicates the variability of the loss tangent of the sample for a given $Re\{\varepsilon_r\}$:

$$\tan\delta = k\left(\frac{1}{Q_l} - \frac{1}{Q_u}\right). \tag{4}$$

The imaginary part of the permittivity is related to the loss tangent by

$$\tan\delta = \frac{\mathrm{Im}\left[\varepsilon_{\mathrm{r}}\right]}{\mathrm{Re}\left[\varepsilon_{\mathrm{r}}\right]} + \frac{\sigma}{\omega\,\mathrm{Re}\left[\varepsilon_{\mathrm{r}}\right]} \approx \frac{\mathrm{Im}\left[\varepsilon_{\mathrm{r}}\right]}{\mathrm{Re}\left[\varepsilon_{\mathrm{r}}\right]}, \tag{5}$$

where σ is conductivity and ω is the measurement frequency. The quantity $\sigma/\omega\, Re\{\varepsilon_{\mathrm{r}}\}$ is assumed to be negligible at RF. Thus, $Im\{\varepsilon_{\mathrm{r}}\}$ is calculated by combining equations 4 and 5 into

$$\mathrm{Im}\left[\varepsilon_{\mathrm{r}}\right] = k\left(\frac{1}{Q_l} - \frac{1}{Q_u}\right)\mathrm{Re}\left[\varepsilon_{\mathrm{r}}\right]. \tag{6}$$

1.4 Advantages and Disadvantages of the Ring-Resonator Technique

The ring-resonator method is able to measure solids as well as liquids. The sample need not be milled (e.g. to fit a coaxial-line or air-gap holder), but it must be flattened or cut along one side such that flush contact is maintained between the resonator and the sample during the measurement. Since the ring resonator measures the permittivity of the dielectric within approximately ½ in of the ring (see appendix B), and since a typical ring measures 3 in × 3 in, only about 4.5 in^3 of each sample are needed.

After the network analyzer is calibrated, the time required to (a) prepare a sample on top of the ring, (b) record a wideband trace, and (c) calculate the real and imaginary parts of the permittivity is usually under 2 min for a single ring resonator. Because spatial variations in permittivity (e.g., due to different soil grain sizes in one sample) are not averaged within individual measurements, multiple trials for each data point must be taken and then averaged to generate an aggregate value for ε from a sample with spatial variations in ε.

Perhaps the most important advantage of the ring-resonator technique is that it does not require the dielectric sample to be displaced from its original location in order to be measured, so that measurements may be made in-situ. Samples need not be preserved or transported. The number of measurements that may be taken in-situ is limited only by the available memory of the data collection system.

2. Ring-Resonator Circuit Boards

2.1 Basic Ring Design

The ring resonators were designed assuming (a) the input and output ports would interface to a 50-Ω network analyzer to measure $|S_{21}|$, and (b) the rings would be printed in copper on top of Rogers 4350B because this metallization and board material are relatively cheap and readily available. Figure 6 is a drawing of the simulated ring design.

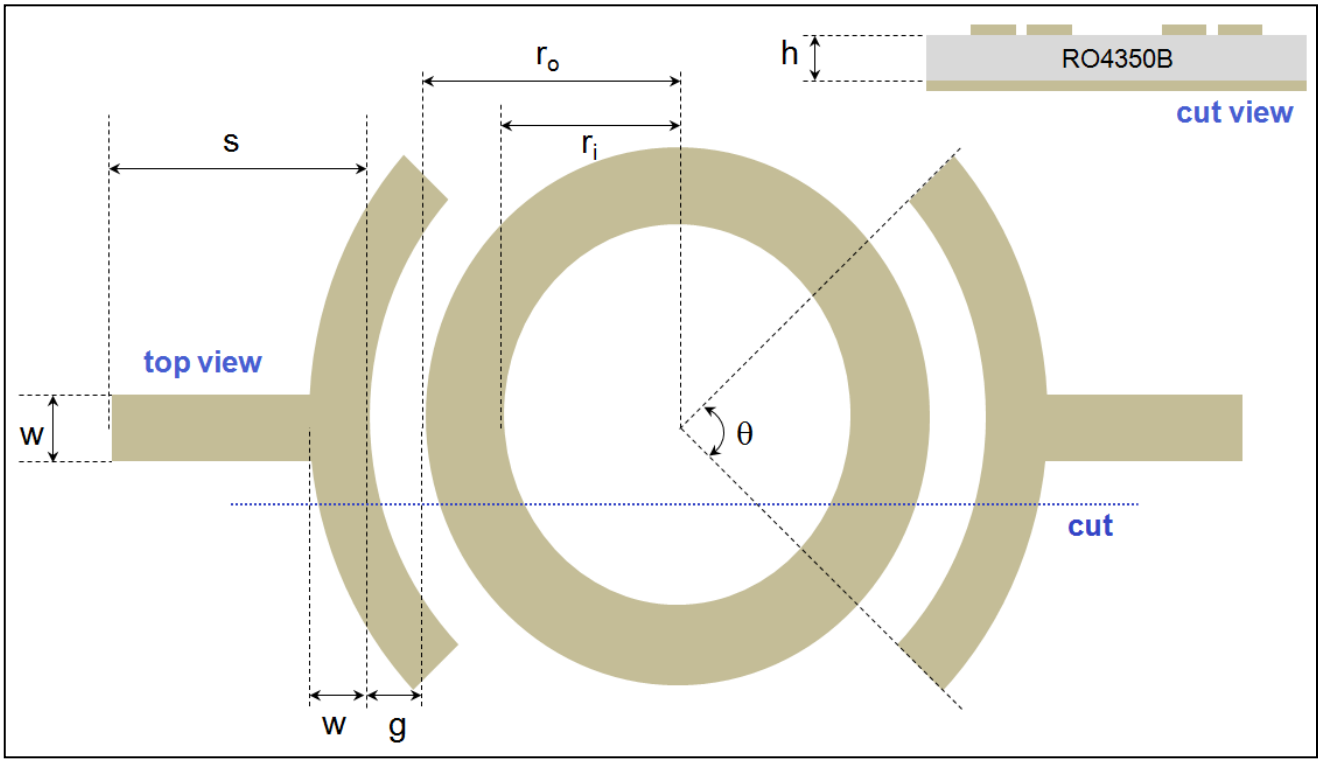

Figure 6. Ring-resonator drawing and dimensions.

To determine the microstrip dimensions necessary to form a 50-Ω line on Rogers 4350B, the following relationships between board height *h*, PCB dielectric ε_r, line-width *w*, and characteristic impedance Z_0 were used (*3*):

$$Z_0 = Z_0^{\text{air}} \Big/ \sqrt{|\varepsilon_{\text{eff}}|} \tag{7}$$

$$Z_0^{\text{air}} = 60 \ln\left[\frac{F_1 h}{w} + \sqrt{1+\left(\frac{2h}{w}\right)^2}\right] \tag{8}$$

$$F_1 = 6 + (2\pi - 6)\exp\left\{-(31h/w)^{0.7528}\right\} \tag{9}$$

$$|\varepsilon_{\text{eff}}| = \frac{\varepsilon_r + 1}{2} + \left(\frac{\varepsilon_r - 1}{2}\right)\left(1 + \frac{10h}{w}\right)^{-a \cdot b} \tag{10}$$

$$a = 1 + \frac{1}{49}\ln\left[\frac{(w/h)^4 + \{w/(52h)\}^2}{(w/h)^4 + 0.432}\right] + \frac{10}{187}\ln\left[1 + \left(\frac{10w}{181h}\right)^3\right] \tag{11}$$

$$b = 0.564\left[\frac{\varepsilon_r - 0.9}{\varepsilon_r + 3}\right]^{0.053}. \tag{12}$$

Combining equations 7 through 12, assuming ε_r = 3.66 and h = 20 mil for Rogers 4350B (*4*), and sweeping w from 0.25 to 2.25 mm, the plot of Z_0 vs. w in figure 7 is obtained. The line-width that most nearly results in a predicted impedance of 50 Ω for this microstrip configuration is w = 1.113 mm. Solutions for other PCBs may be found by substituting the appropriate values for ε_r and h.

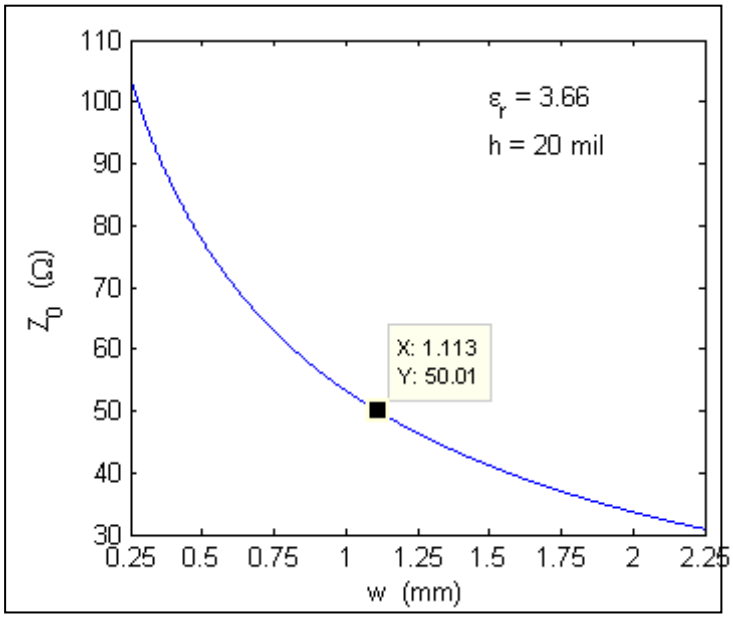

Figure 7. Predicted characteristic impedance Z_0 of Rogers 4350B microstrip as a function of conductor line-width w.

The guided wavelength of RF in the microstrip at a particular design frequency is found by rearranging equation 2:

$$\lambda_g = \frac{c}{f_0\sqrt{|\varepsilon_{\text{eff}}|}}, \tag{13}$$

where the value of ε_{eff} is taken from equation 9. For a design frequency of 900 MHz, the average ring radius is

$$r_{\text{avg}} = \frac{n\lambda_g}{2\pi} = \frac{n\cdot c}{2\pi\cdot f_0\sqrt{|\varepsilon_{\text{eff}}|}} = \frac{(1)\left(3\cdot 10^8\right)}{(2\pi)\left(900\cdot 10^6\right)\sqrt{2.86}} = 31.37\text{ mm}, \tag{14}$$

thus the inner and outer radii of the ring are calculated to be

$$r_i = r_{\text{avg}} - w/2 = 31.37\text{ mm} - 0.56\text{ mm} = 30.81\text{ mm} \tag{15}$$

$$r_o = r_{\text{avg}} + w/2 = 31.37\text{ mm} + 0.56\text{ mm} = 31.93\text{ mm}. \tag{16}$$

The 900-MHz ring was initially simulated in FEKO version 5.5 using an input/output feedline length s of one quarter-wavelength:

$$s = \lambda_g / 4 = (197.2\ \text{mm}) / 4 = 49.3\ \text{mm}. \tag{17}$$

To lower the insertion loss of the structure by increasing the capacitive coupling between the feedlines and the ring, the ends of the feedlines nearest the ring were extended into arcs (*5*). The lengths of the arcs are bounded by the angle θ.

2.2 Simulation in FEKO

Resonators with different coupling-gap widths g were simulated in order to determine the optimum spacing between the feedlines and the ring. The fundamental resonant mode of the 900-MHz ring is plotted for five different coupling gaps in figure 8. A loss tangent of 0.0031 was assumed for Rogers 4350B (*4*).

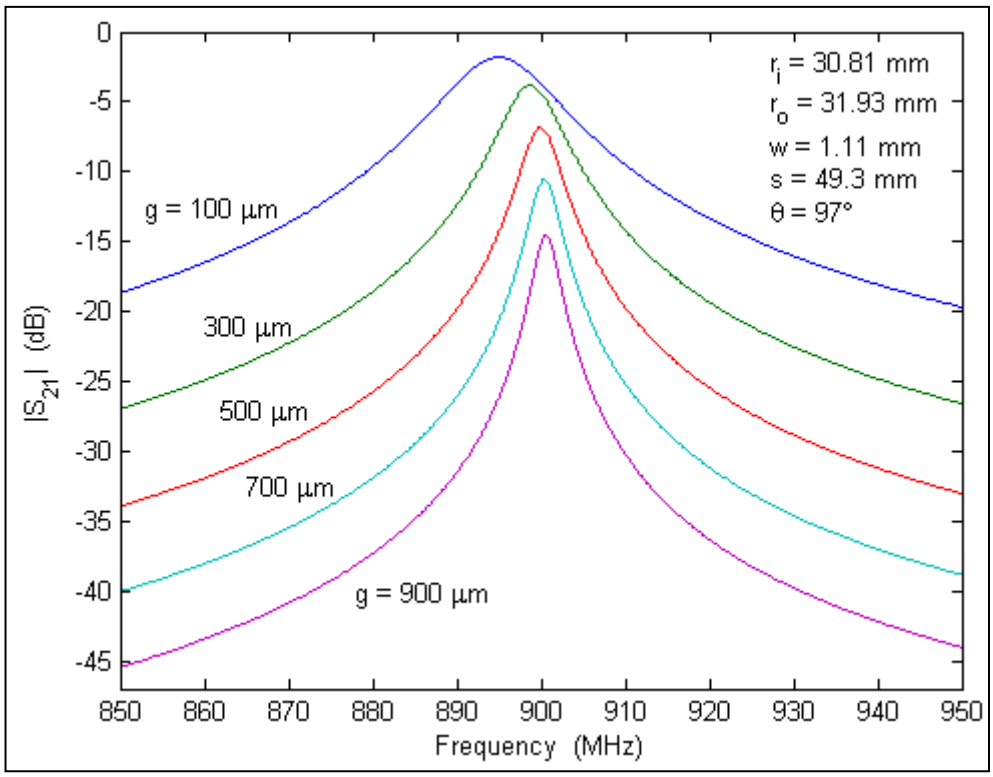

Figure 8. Variation in the first resonant mode of a 900-MHz ring as a function of gap width g.

Although a thinner gap increases coupling between the feedlines and the ring, the gap cannot be made infinitesimally small. For values of g under 500 µm, the resonance of the ring begins to deflect from the desired frequency and the quality factor of the peak begins to lower. As a compromise between low insertion loss and minimal deflection of the resonance from its desired peak, a gap width of g = 555 µm was selected for further design.

To determine the optimum lengths for the feedline arcs, resonators with different arc angles, θ, were simulated. The fundamental resonant mode of the 900-MHz ring is plotted for six different arc angles in figure 9.

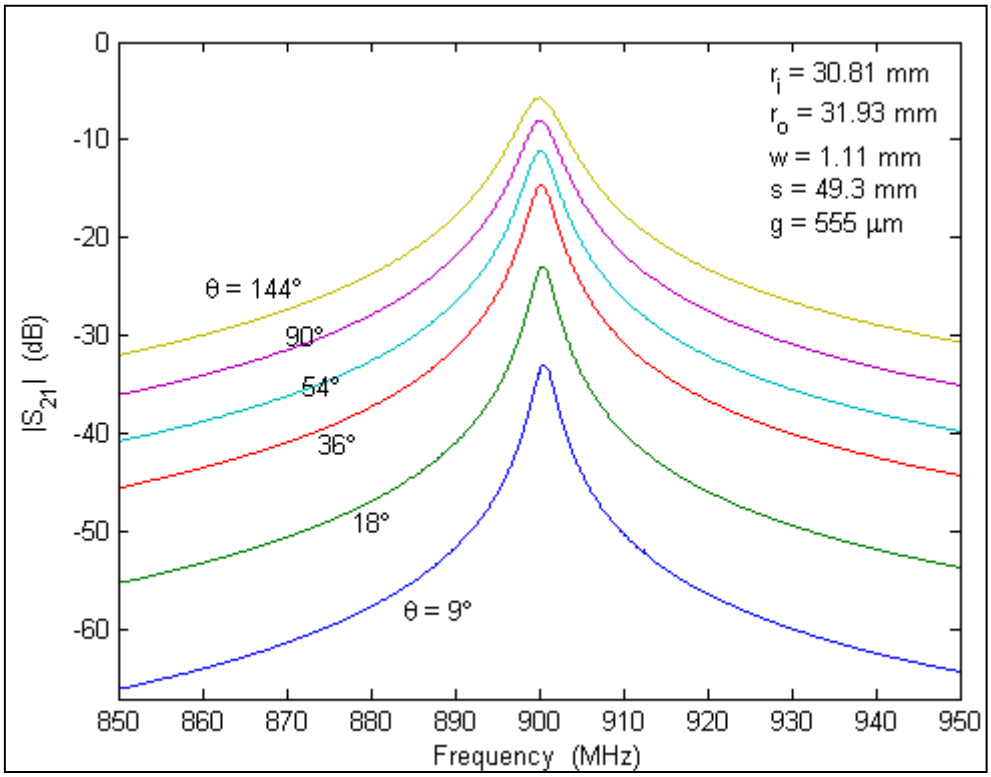

Figure 9. Variation in the first resonant mode of a 900-MHz ring as a function of arc angle θ.

Longer arcs result in a lower insertion loss. With the gap width held constant, there is no deflection of the resonance from the desired frequency for longer arcs. Unfortunately, the quality factor is lower for arcs that nearly encompass the ring. As a compromise between low loss and minimal quality factor reduction, an arc angle of $\theta = 85°$ was selected for further design.

2.3 Fabricated Rings

Ring resonators with f_0 = 600, 900, 1200, and 1500 MHz were fabricated using copper traces on a Rogers 4350B substrate. $|S_{21}|$ for the unloaded rings was measured using the Rhode & Schwarz ZVB-8 vector network analyzer (VNA). The measured $|S_{21}|$ for the 600- and 900-MHz rings is shown in figure 10. A picture of the 900-MHz resonator is given in figure 11.

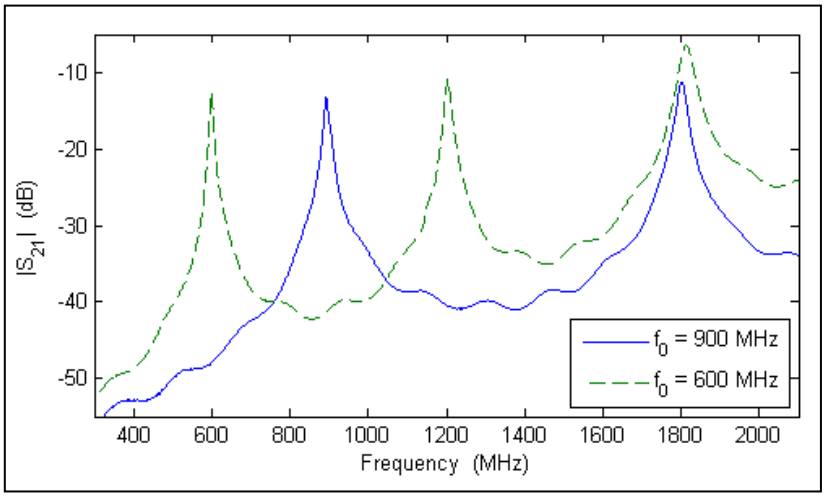

Figure 10. Measured $|S_{21}|$ for unloaded 600-MHz and 900-MHz ring resonators.

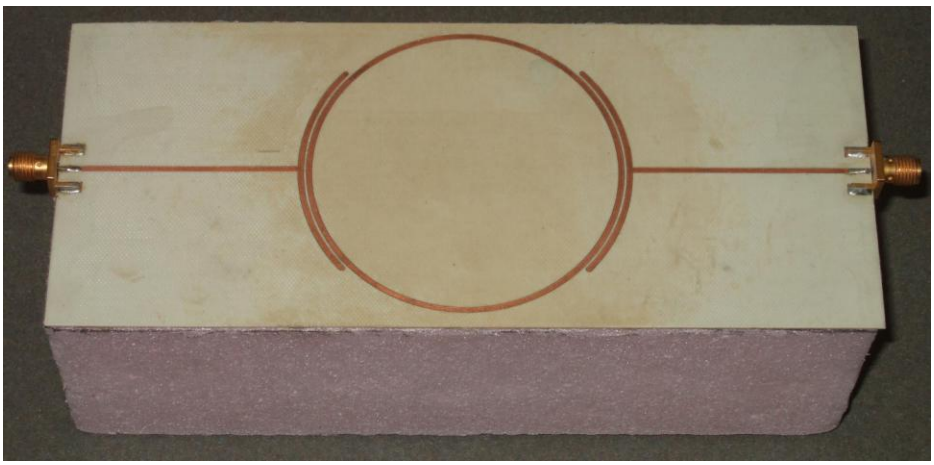

Figure 11. Picture of fabricated, unloaded 900-MHz ring resonator: a block of foam is glued to the underside of the PCB for rigidity (because the Rogers 4350B board, at h = 20 mil, is easily snapped).

The design dimensions for eight ring resonators with fundamental frequencies between 600 and 2000 MHz are listed in table 1.

Table 1. List of dimensions for simulated and fabricated ring-resonator designs: each design measures 6 inches across (from input to output).

h **(mil)**	***θ*** **(deg)**	***g*** **(mm)**	***w*** **(mm)**
20	85	0.555	1.113

f_0 **(MHz)**	***r_i*** **(mm)**	***r_o*** **(mm)**	***s*** **(mm)**
600	46.647	47.760	27.886
900	30.891	32.004	43.642
1100	25.173	26.286	49.360
1200	23.024	24.137	51.509
1300	21.215	22.328	53.318
1400	19.629	20.742	54.904
1500	18.274	19.387	56.259
2000	13.483	14.596	61.050

3. Meander-Line Ring Resonators

Microstrip ring resonators are typically used to measure the permittivity of dielectric samples at frequencies above 1 GHz (*2, 6, 7*). Dielectrics measured by ring resonators whose permittivity values are reported in the literature include wet and dry sand (*2*), plastic (*6*), clay (*6*), paper (*7*), and wheat grains (*7*), between 1 and 12 GHz. Measurements at lower frequencies are impractical for the traditional resonator design because the circumference of the ring is prohibitively large below 1 GHz. At such frequencies, maintaining flush contact between the resonator and the sample is difficult or impossible.

To enable permittivity measurements with ring resonators at radio frequencies, the surface area within each resonator has been compacted by meandering the circumference of each ring. Although the path length of the microstrip ring is the same before and after meandering the line, the area enclosed by the microstrip is reduced in the meander-line case, by $A_t / A_m = F$. The PCB area required to fabricate the microstrip geometry is reduced by F. While the depth of the dielectric sample required for measurement remains unchanged, the area of the sample that contacts the resonator is reduced by F, so the volume of the sample is reduced by F.

Figure 12a is a picture of two types of ring resonators that were drawn in FEKO. Figure 12b is a picture of the actual resonators, fabricated on Rogers 4350B microstrip board, corresponding to these drawings. On the left-hand side of each figure is the traditional ring-resonator structure; on the right-hand side is the more compact meander-line form.

For a specified PCB dielectric, microstrip geometry, and coupling gap spacing, the path length of the meandered line is set equal to the circumference of the traditional loop. Since the ring length is the same between the two designs, and since neither ring conductively contacts its input and

output feedlines, the voltage standing wave patterns established along each ring are the same and, therefore, the resonant frequencies are the same.

Figure 13 shows the simulated and measured transmission coefficients of the four ring resonators from figure 12. Each ring resonates near 350 MHz. Deviations from 350 MHz are caused by non-zero tolerances in the microstrip width, board height, and PCB dielectric. Higher insertion loss observed in the meander-line design is due to coupling between the anti-parallel transmission lines interior to the ring and multi-moding generated at the bends in the meandered line.

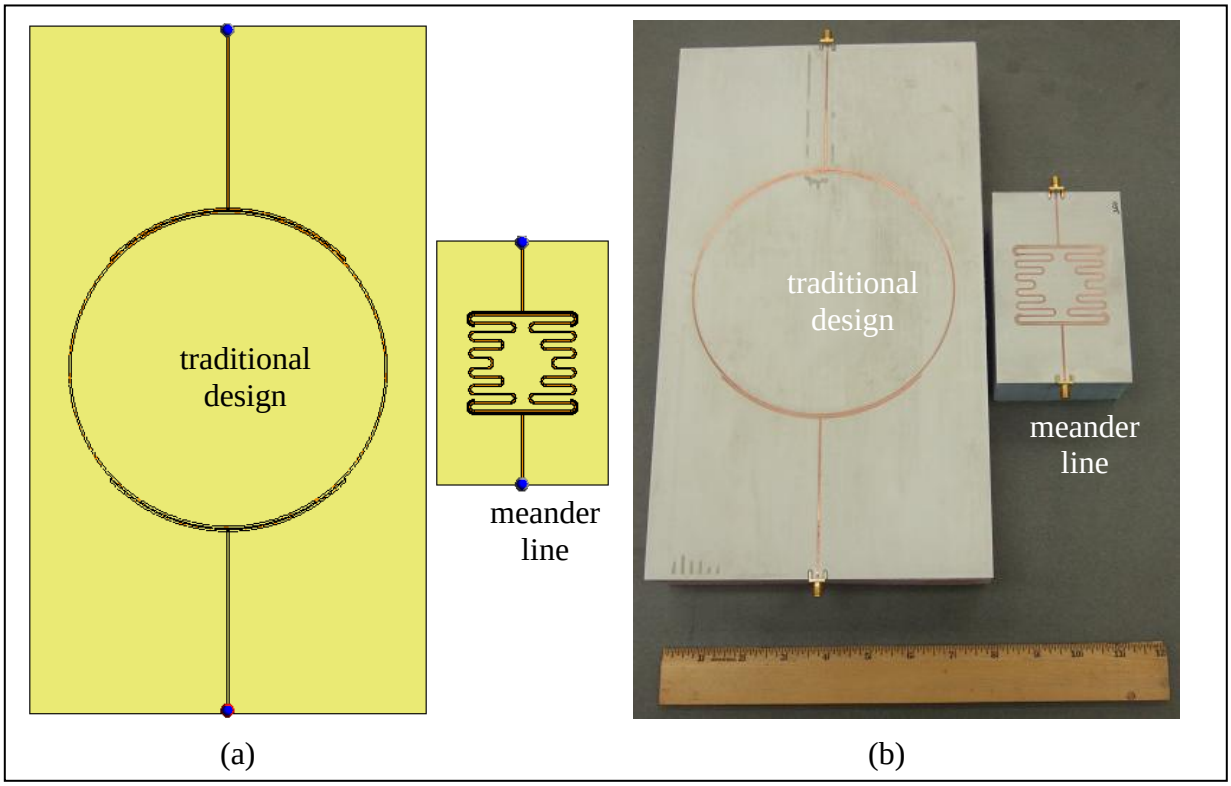

Figure 12. Traditional ring-resonator structure vs. compact meander-line structure: (a) drawings in FEKO, (b) picture of fabricated resonators.

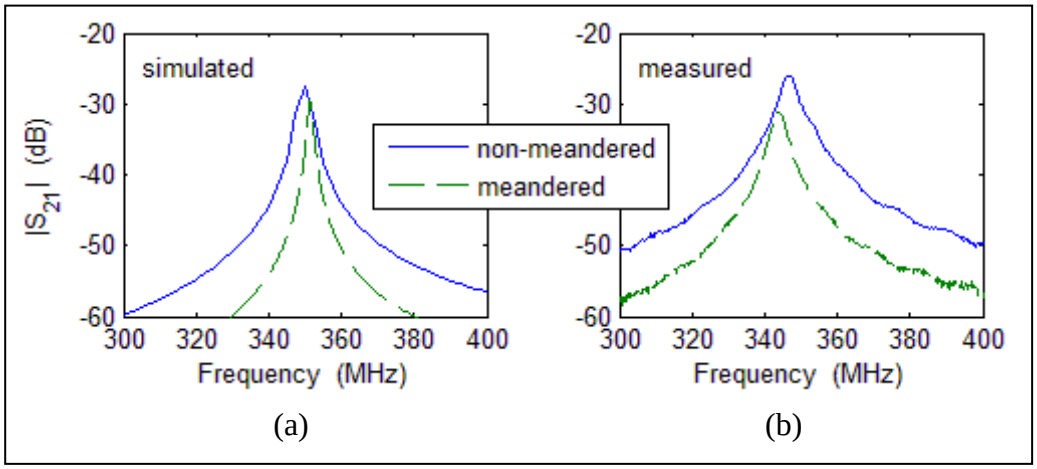

Figure 13. Transmission coefficients for traditional and meander-line ring resonators: (a) simulated in FEKO, (b) measured using network analyzer.

The surface area within the traditional 350-MHz Rogers 4350B 50-Ω ring is

$$A_t = \pi r^2 = \pi \cdot (8.15\,\text{cm})^2 = 209\,\text{cm}^2, \tag{18}$$

while the surface area within the meander-line 350-MHz Rogers 4350B 50-Ω ring is approximately

$$A_m \approx l_{max} \cdot w_{max} = (5.1\,\text{cm})(5.6\,\text{cm}) = 29\,\text{cm}^2, \tag{19}$$

where l_{max} and w_{max} are the maximum length and width measured across the fingers of the meander-line ring. The area within the perimeter of the ring is reduced by a factor of

$$F = A_t / A_m = 209\,\text{cm}^2 / 29\,\text{cm}^2 = 7.3 \tag{20}$$

by meandering the ring. It should be noted that this value for F is not the maximum that may be achieved. Further area reduction is possible for the same resonant frequency and 50-Ω line impedance by (a) thinning the microstrip lines while using a higher PCB dielectric, and (b) reducing the distance between each finger of the meander-line. Both of these compactions will result in higher insertion loss for the overall structure.

Figure 14 shows FEKO drawings of meander-line designs for four additional frequencies: 250 MHz, 300 MHz, 400 MHz, and 550 MHz. Figure 15 contains pictures of four realizations of these resonators, fabricated on Rogers 4350B substrate.

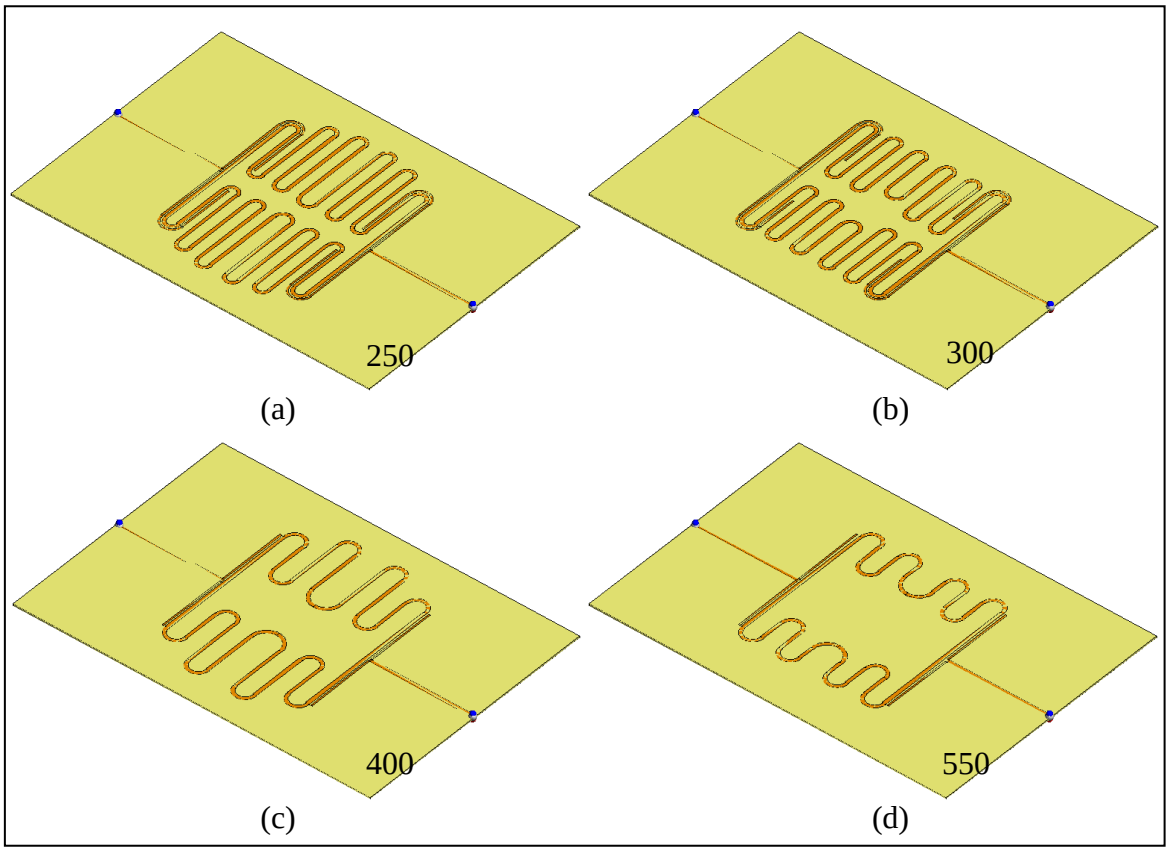

Figure 14. FEKO drawings of meander-line rings at 4 different fundamental frequencies: (a) 250 MHz, (b) 300 MHz, (c) 400 MHz, and (d) 550 MHz.

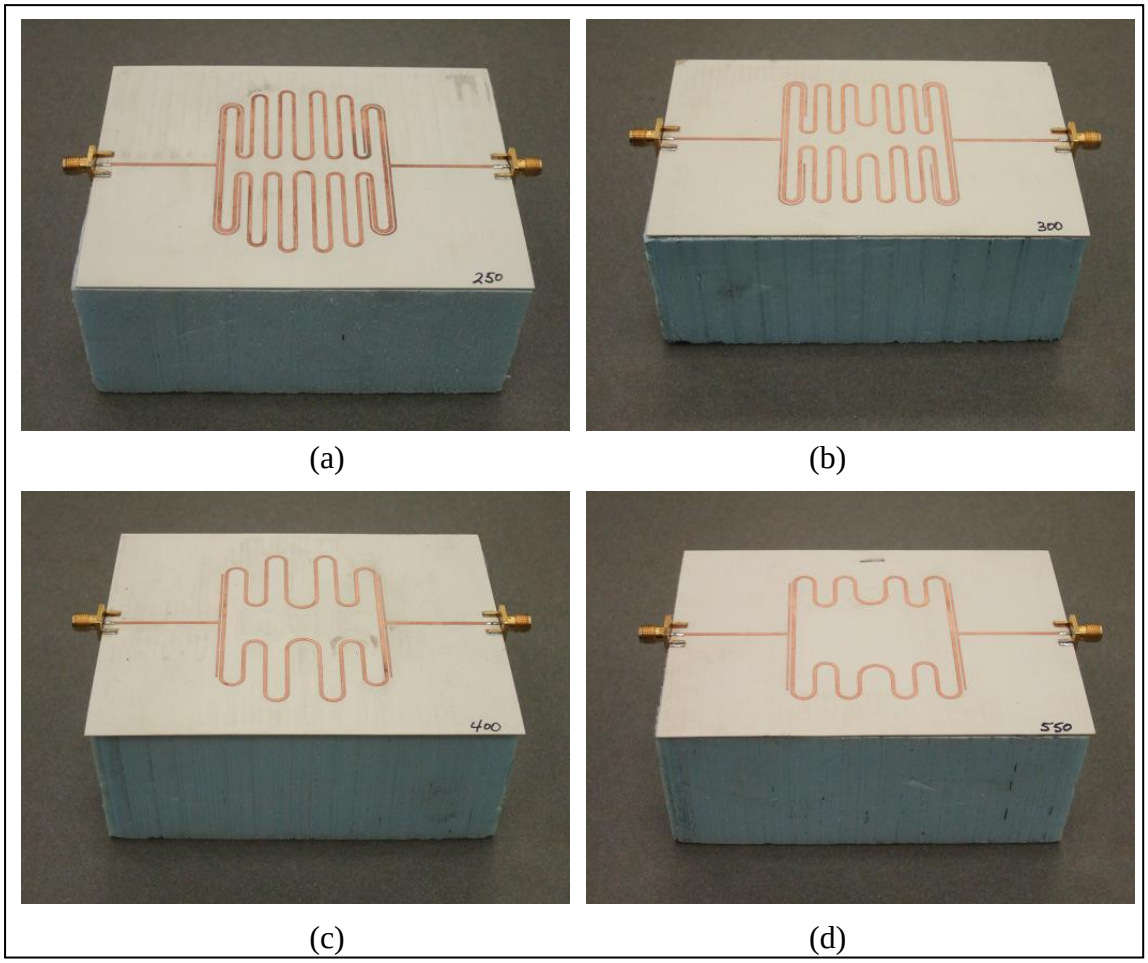

Figure 15. Pictures of meander-line rings fabricated from the FEKO designs in figure 14: (a) 250 MHz, (b) 300 MHz, (c) 400 MHz, and (d) 550 MHz.

The greatest area reduction achieved between the traditional design and the meander-line design is for the lowest frequency realized thus far, 250 MHz:

$$\begin{aligned} A_{\mathrm{t}} &= \pi \cdot (11.4\ \mathrm{cm})^2 = 292\ \mathrm{cm}^2 \\ A_{\mathrm{m}} &= (5.1\ \mathrm{cm})(7.1\ \mathrm{cm}) = 36\ \mathrm{cm}^2 \\ F &= 292\ \mathrm{cm}^2 / 36\ \mathrm{cm}^2 = 8.1 \quad . \end{aligned} \tag{21}$$

Simulations of all five designs in FEKO and measurements of all five realizations using the Agilent FieldFox N9923A VNA confirm that these rings resonate at the intended frequencies. Traces of the simulation and measurement data that show the corresponding resonances for each ring are provided in figure 16.

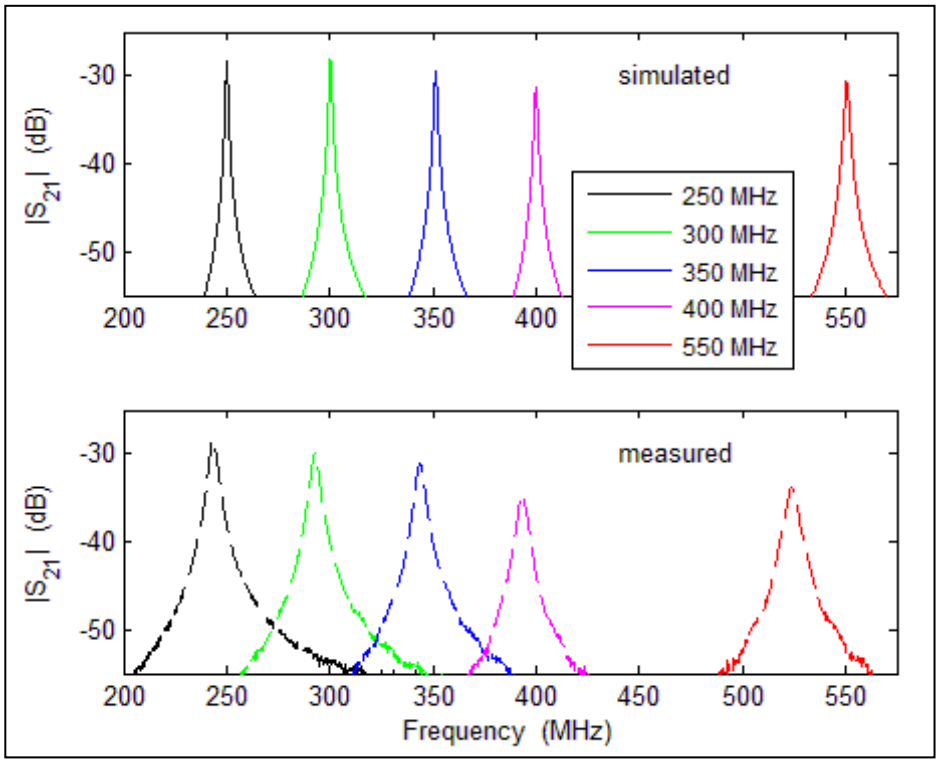

Figure 16. Transmission coefficients for the ring resonators shown in figures 14 and 15: (a) simulated in FEKO v.5, (b) measured using the Agilent FieldFox N9923A.

4. Procedure for Measuring Permittivity: Full System

The full portable system used to measure permittivity between 250 MHz and 4 GHz consists of the following pieces of equipment:

- six ring resonators: 250 MHz, 1200 MHz, 1300 MHz, 1400 MHz, 1500 MHz, and 2000 MHz
- handheld network analyzer: Agilent N9923A ("FieldFox")
- pair of Subminiature version A (SMA) cables
- roll of plastic wrap or wax paper
- laptop: running Matlab, containing "N9923A_ringres" script
- Ethernet local area network (LAN) cable

The network analyzer, SMA cables, and one ring resonator are shown in figure 17.

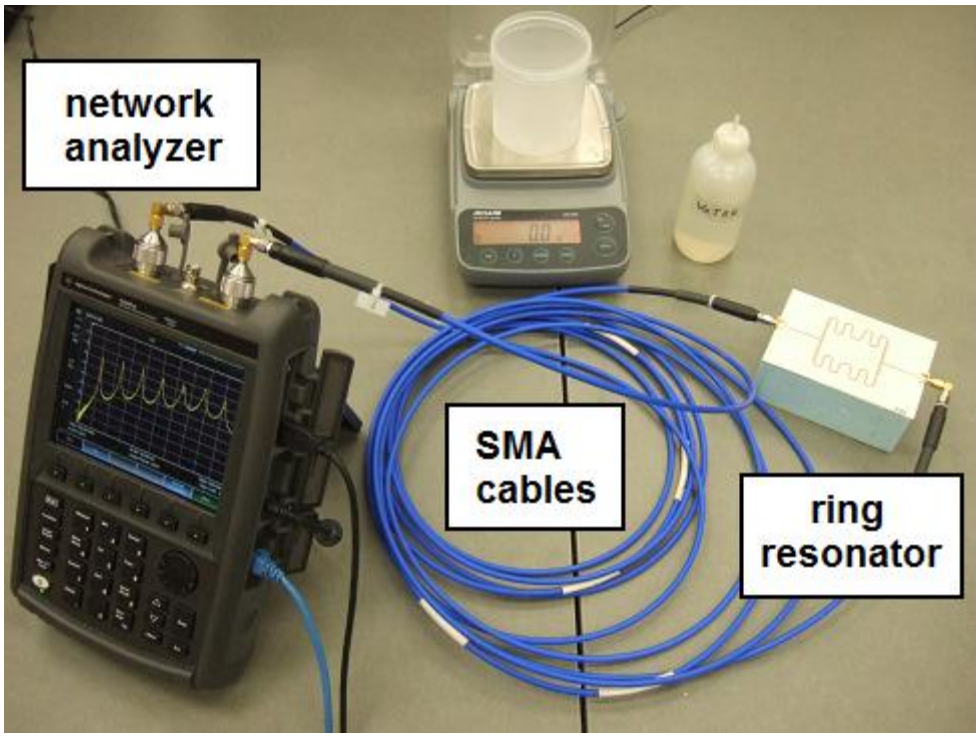

Figure 17. Portable permittivity measurement system components.

The SMA cables connect the input of the ring resonator to Port 1 of the N9923A network analyzer and the output of the ring resonator to Port 2 of the network analyzer. The Ethernet cable connects the LAN port of the N9923A to the LAN port of the laptop (not shown in figure 17).

The permittivity measurement proceeds as follows:

(1) The N9923A is powered up and calibrated. (For step-by-step calibration instructions, see appendix A.)

(2) Matlab is started on the laptop.

(3) In Matlab, the "N9923A_ringres" script is executed. The graphical user interface (GUI) of figure 18 appears.

(4) The user selects the frequency range ("Min Frequency", "Max Frequency") and frequency resolution ("Resolution (points)"). It is recommended that the maximum frequency for the measurement be set no greater than 7× the fundamental resonance of the highest-frequency ring to be used, and that the number of points be set so that the frequency resolution is no greater than 3 MHz.

(5) The user selects the ring resonator to be used for the measurement (e.g., "400") under "Ring Frequency (MHz)".

(6) The surface of the ring resonator is kept clean (no sample) and the user clicks the "Acquire data from N9923A: No sample" button in the GUI. $|S_{21}|$ versus frequency is recorded for the unloaded resonator (in blue).

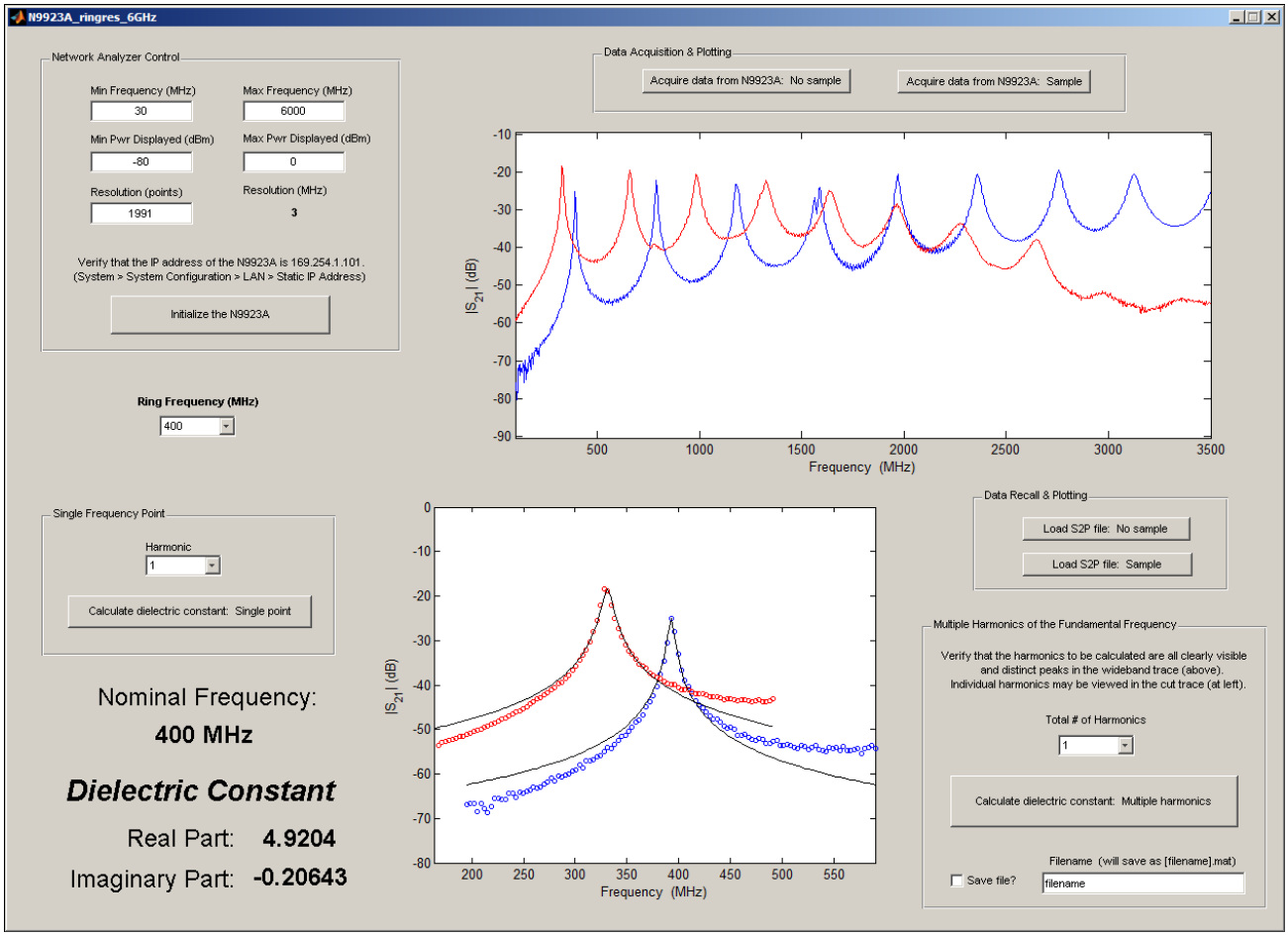

Figure 18. GUI for the "N9923A_ringres" measurement application in Matlab.

(7) The sample is placed on top of the resonator (or the resonator is placed on top of the sample). Flush contact is made between the resonator and the sample. The dielectric sample must be large enough to completely cover the microstrip ring. The sample must be at least a half-inch thick for ring resonators printed on Rogers 4350B. (For an explanation of this minimum thickness, see appendix B.)

Note: An aluminum weight may be placed on top of the sample/resonator to ensure flush contact between the resonator and the sample, as seen in figure 19. Here, a soil sample is contained in a single sheet of plastic-wrap.

(8) The user clicks the "Acquire data from N9923A: Sample" button in the GUI. $|S_{21}|$ is recorded for the loaded resonator (in red).

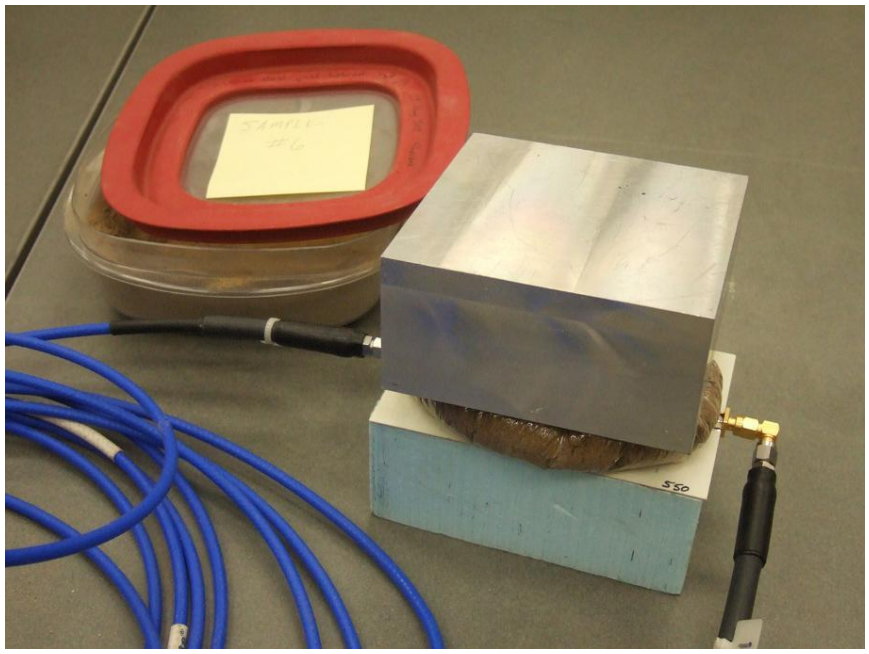

Figure 19. Loaded resonator: soil sample placed in baggie, baggie placed on resonator, aluminum weight placed on baggie.

(9) To calculate ε for each harmonic of the 400-MHz resonance individually, the user sets "Harmonic" in the "Single Frequency Point" panel and then clicks "Calculate Dielectric Constant: Single Point". A single pair of peaks, cut from the full data set, appears to the right of the "Single Frequency Point" panel. The real and imaginary parts of the dielectric constant are calculated from this cut and their values appear below the "Single Frequency Point" panel.

(10) To calculate ε for a collection of harmonics (instead of one at a time), the user sets "Total # of Harmonics" in the "Multiple Harmonics of the Fundamental Frequency" panel and then clicks "Calculate Dielectric Constant: Multiple Harmonics." The real and imaginary parts of ε are calculated for each pair of resonant peaks, starting at the fundamental resonance of the ring and ending at the number of the harmonic set by the user (up to six). When the calculation is complete for the selected harmonics, a new window opens, which contains a plot of $Re\{\varepsilon\}$ and $Im\{\varepsilon\}$ versus frequency for the sample and the harmonics of the resonant frequency that were requested. Figure 20 contains a screenshot of this new window.

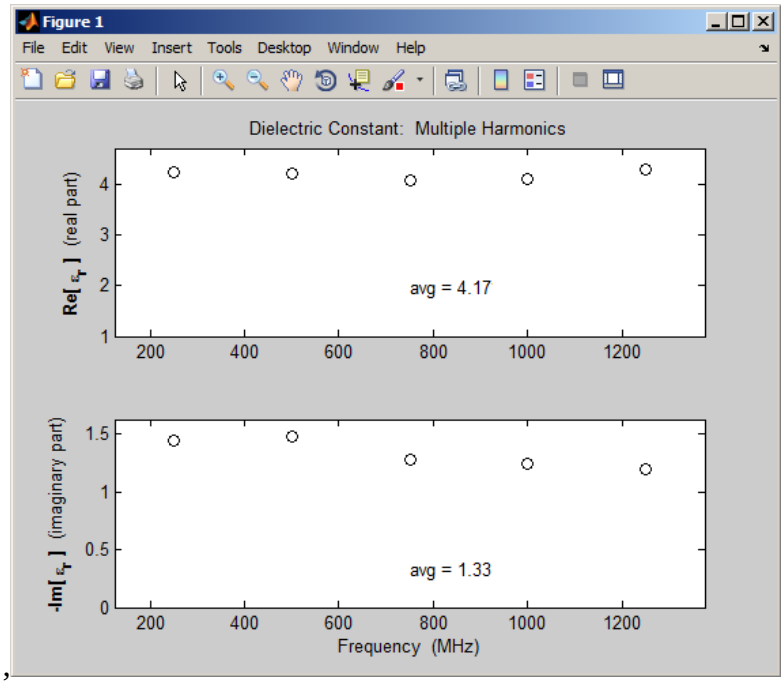

Figure 20. Window that appears after permittivity at the multiple harmonics of the ring resonance is calculated.

Note: Checking the box in front of "Save file?" will direct Matlab to save the values for frequency, $Re\{\varepsilon\}$, and $Im\{\varepsilon\}$ (plotted in the new Figure window) into a .MAT file whose name is specified by "Filename". The file will be located in Matlab's current "work" directory. Stored in each .MAT file are three vectors: one containing frequency values at integer harmonics (e.g. 400, 800, 1200), one containing the $Re\{\varepsilon\}$ values measured at these harmonics, and one containing the $Im\{\varepsilon\}$ values measured at these harmonics.

5. Procedure for Measuring Permittivity: No PC Available

If a computer running Matlab is not immediately available (or convenient for in-situ measurements), the raw $|S_{21}|$ data may be collected and the permittivity of the sample calculated separately.

The permittivity measurement proceeds as follows:

(1) The N9923A is powered up.

(2) A keyboard is connected to the N9923A via Universal Serial Bus (USB).

(3) The user sets the measurement parameters for the individual $|S_{21}|$ traces:

a. On the N9923A, press "up-arrow", then "Measure" (number 1). Select "S21".

b. Press “up-arrow”, then “Sweep” (number 3). Select “Resolution”. Select the desired frequency resolution (points). The recommended value is the maximum: “1001”.

c. Press “Freq/Dist”. Select “Start”. Enter the desired starting frequency.

d. Press “Stop”. Enter the desired ending frequency. It is recommended that the ending frequency be set no greater than 7x the fundamental resonance of the highest-frequency ring to be used.

(4) The N9923A is calibrated. (For step-by-step calibration instructions, see appendix A.)

(5) The user sets the trace-save format to S2P:

a. On the N9923A, press “up-arrow”, then “Save/Recall” (number 9).

b. Select “File Type”. Select “Data (S2P)”.

(6) The input port of a ring resonator is connected to Port 1 of the N9923A, and the output port of the ring resonator is connected to Port 2. (Since each ring resonator is reciprocal, either port may be designated as “input” or “output”. However, it is recommended that the designation be kept consistent for all measurements that use the same ring resonator.)

(7) The user records a data trace with the sample absent:

a. Keep the surface of the resonator clean. (i.e. Keep the space above the ring empty).

b. On the N9923A, press “up-arrow”, then “Save/Recall” (number 9).

c. Select “Save”. Give the trace an appropriate label. Denote “no sample”. Include the fundamental frequency of the resonator in the filename. Press “Done”.

(8) The user records a data trace with the sample present:

a. If using plastic wrap or wax paper to protect the resonators from contamination by the sample, place a single sheet on top of the resonator. The sheet must be wide enough and long enough to completely cover the microstrip ring, but it does not necessarily need to cover the input/output feedlines.

b. Place the dielectric sample on top of the plastic/wax sheet. The dielectric sample must be large enough to completely the cover the microstrip ring. The sample must be at least a half-inch thick for ring resonators printed on Rogers 4350B. (For an explanation of this minimum thickness, see appendix B.)

c. To ensure flush contact between the resonator-plastic-sample layering, place an aluminum weight on top of the sample.

d. On the N9923A, press “up-arrow”, then “Save/Recall” (number 9).

e. Select “Save”. Give the trace an appropriate label. Denote the material being measured. Include the fundamental frequency of the resonator in the filename. Press “Done”.

Note: By pressing “up-arrow” then “Run/Hold”, the trace can be frozen before it is recorded. Press “Run/Hold” again to release the trace before recording another.

(9) Step (8) is repeated for each sample to be recorded by the resonator. Steps (6) through (8) are repeated for each ring resonator of interest.

(10) The user copies the data traces stored internal to the network analyzer onto a USB stick:

a. Connect a thumb-drive via USB to the N9923A.

b. On the N9923A, press “up-arrow”, then “Save/Recall” (number 9). Select “More”.

c. Select “Manage Files”. Select “Copy All Files”. Select “Copy to USB”.

(11) The user moves the S2P data files from the USB stick onto the computer running Matlab.

(12) Matlab is started, “N9923A_ringres” is executed, and the GUI of figure 18 appears.

(13) The user imports the S2P files and the dielectric constant of the sample is calculated:

a. In the “Data Recall & Plotting” panel of the GUI, click “Load S2P file: No sample”. Locate the S2P file containing the empty-resonator trace recorded during Step (7). Click “OK” to load this trace into the upper plot window (in blue).

b. Click “Load S2P file: Sample”. Locate the S2P file containing the sample trace recorded during Step (8). Click “OK” to load this trace into the upper plot window (in red).

c. Under “Ring Frequency (MHz)”, select the ring resonator that was used for the measurement.

d. To calculate ε for each harmonic of the ring’s fundamental resonance individually, set “Harmonic” in the “Single Frequency Point” panel and then click “Calculate Dielectric Constant: Single Point”. A single pair of peaks, cut from the full data set, appears to the right of the “Single Frequency Point” panel. The real and imaginary parts of the dielectric constant are calculated from this cut, and their values appear below the “Single Frequency Point” panel.

e. To calculate ε for a collection of harmonics, set “Total # of Harmonics” in the “Multiple Harmonics of the Fundamental Frequency” panel and then click “Calculate Dielectric Constant: Multiple Harmonics.” The real and imaginary parts of ε are calculated for each pair of resonant peaks. When the calculation is complete for all of the selected harmonics, a new Figure window opens that contains a plot of Re{ε} and

Im{ε} versus frequency for the sample and the harmonics of the resonant frequency that were requested.

6. Sample Data

Permittivity values generated by the ring-resonator system are provided in figures 21 through 24. Figures 21 and 22 give ε for two types of real-time-vulcanizing (RTV) rubbers, which are often used as simulants for homemade explosives. Figure 23 gives ε for butterblock, which is sometimes used as a reference or calibration material for permittivity measurement systems. Figures 24 and 25 give ε for two soil samples collected in Yuma, AZ.

For the RTV rubbers, the measured values for ε_r compare well with the values given in the manufacturer's datasheets. Note that to calculate ε_r from $Re\{\varepsilon_r\}$ and $Im\{\varepsilon_r\}$,

$$\varepsilon_r = \sqrt{\left(\mathrm{Re}\{\varepsilon_r\}\right)^2 + \left(\mathrm{Im}\{\varepsilon_r\}\right)^2} \ . \tag{21}$$

For RTV-3110, the measured average value for ε_r is 3.16 and the given value is 3.01 (*8*), which is a 5% difference. For RTV-2, the measured average value for ε_r is 2.9 and the given value is 3.0 (*9*), which is a 3% difference.

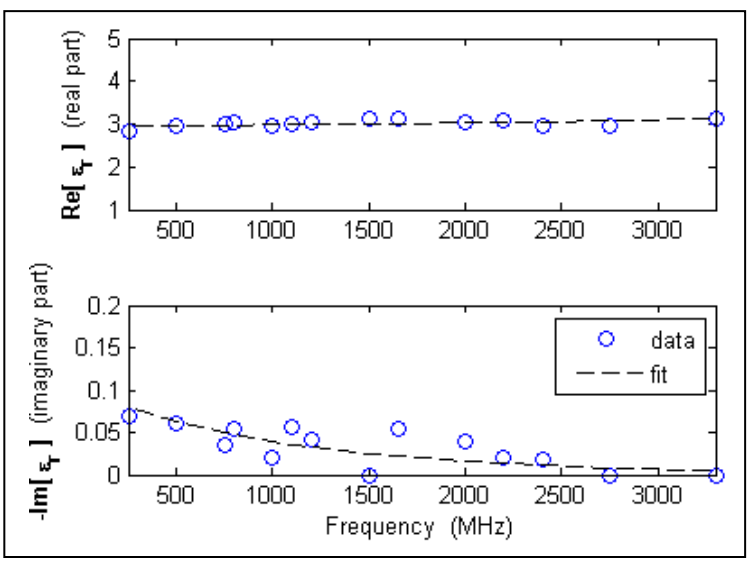

Figure 21. Permittivity measured for RTV-3110 from Dow Corning:

$\mathrm{Re}\{\varepsilon_r\} \approx 2.94 + \left(5.14 \cdot 10^{-5}\right)\left(f/10^6\right)$, average value = 3.01.

$\mathrm{Im}\{\varepsilon_r\} \approx -0.101 \exp\left\{-\left(f/10^6\right)/1074\right\}$, average value = –0.033.

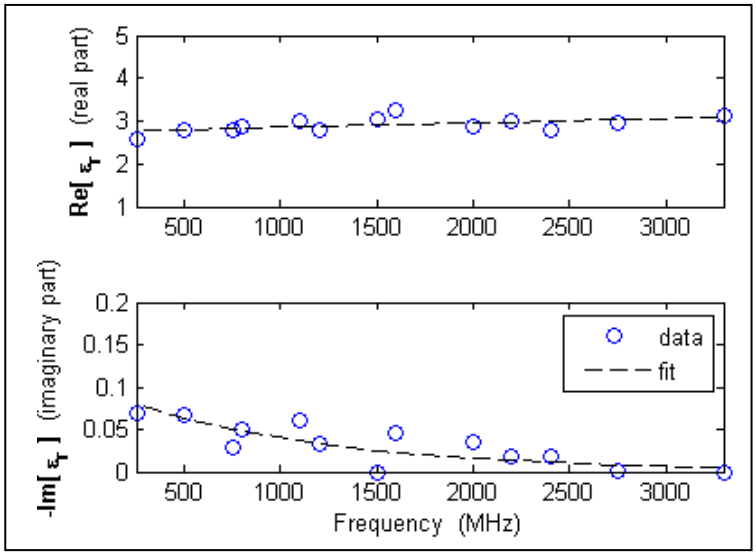

Figure 22. Permittivity measured for RTV-2 (P17) from Silicones, Inc.:

$\mathrm{Re}\{\varepsilon_r\} \approx 2.74 + \left(1.06 \cdot 10^{-4}\right)\left(f/10^6\right)$, average value = 2.91.

$\mathrm{Im}\{\varepsilon_r\} \approx -0.101 \exp\left\{-\left(f/10^6\right)/1079\right\}$, average value = –0.033.

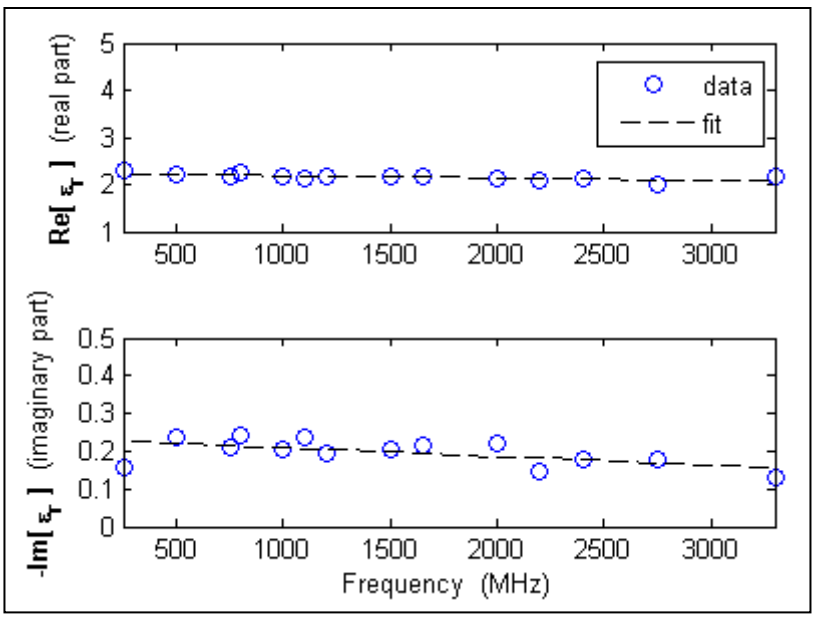

Figure 23. Permittivity measured for butterblock:

$\mathrm{Re}\{\varepsilon_r\} \approx 2.23 - \left(4.93 \cdot 10^{-5}\right)\left(f/10^6\right)$, average value = 2.16.

$\mathrm{Im}\{\varepsilon_r\} \approx -0.229 + \left(2.17 \cdot 10^{-5}\right)\left(f/10^6\right)$, average value = –0.196.

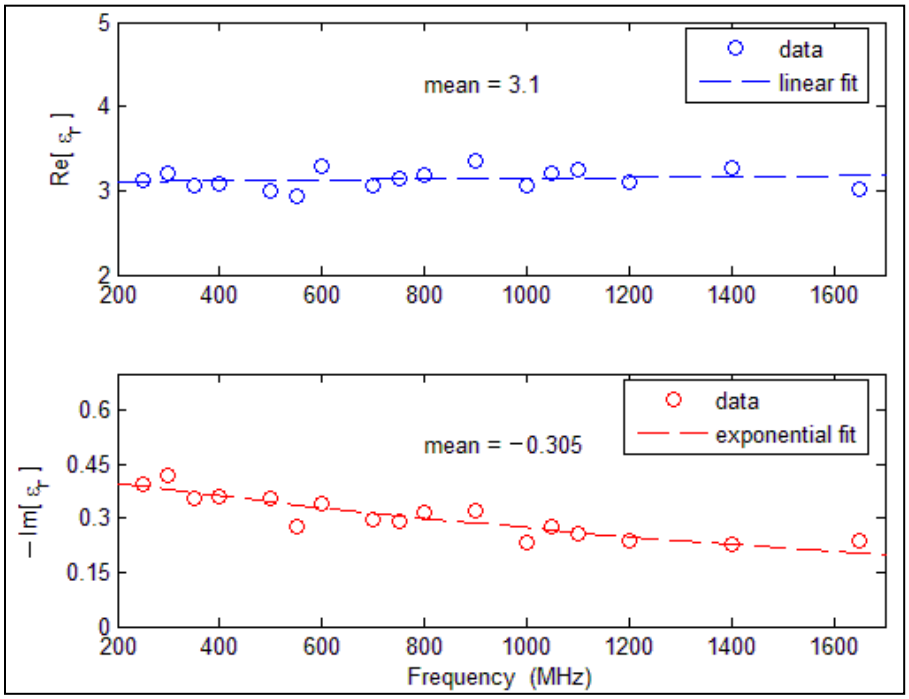

Figure 24. Permittivity measured for soil sample 1 collected at Yuma Proving Ground.

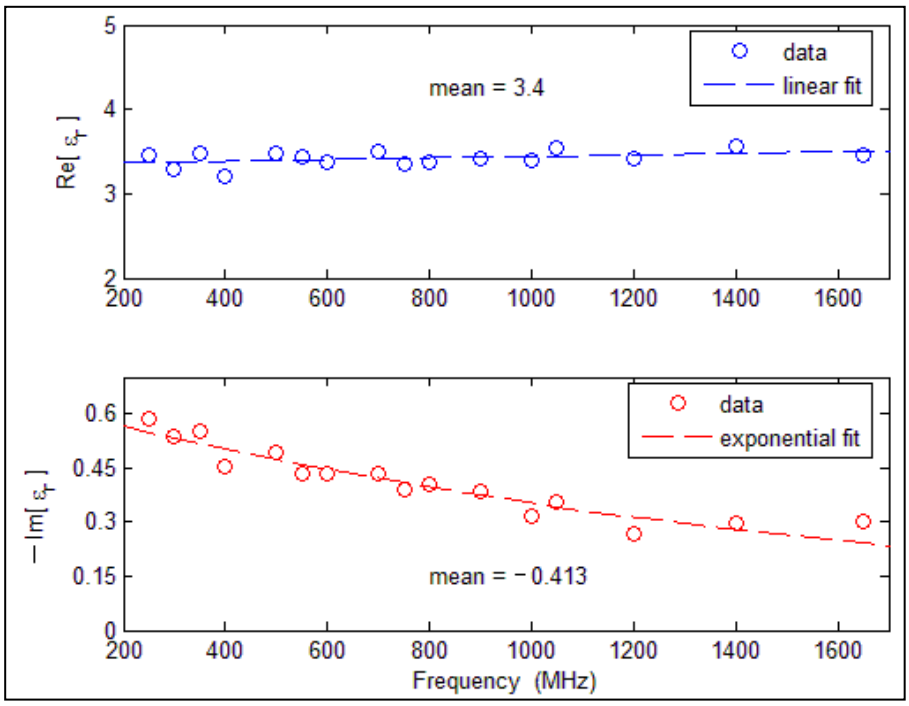

Figure 25. Permittivity measured for soil sample 2 collected at Yuma Proving Ground.

7. Conclusions

The ring-resonator measurement technique provides complex permittivity measurements for many non-magnetic materials relevant to UWB GPR, including dry soils, wet soils, and homemade explosives. The technique is portable, wideband, and can be performed in-the-field, without disturbing the dielectric sample.

Design equations and physical dimensions were presented for fabricating traditional (circular) rings, with fundamental frequencies between 600 MHz and 2 GHz, on a Rogers 4350B substrate. Resonators with fundamental frequencies under 600 MHz were made possible by meandering the microstrip ring.

The measurement procedure was explained, step by step. A handheld VNA records the $|S_{21}|$ traces necessary to determine ε. Only the VNA, cabling, and ring resonator(s) are necessary for the measurement. A Matlab script interpolates along lookup curves generated in FEKO in order to calculate ε. Values for $Re\{\varepsilon\}$ and $Im\{\varepsilon\}$ can be generated after each sample is measured, or they can be generated after all of the samples have been measured. Data was presented for samples of soils and homemade explosive simulants.

8. References

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5. Chang, K.; Hsieh, L. H. Modes, Perturbations, and Coupling Methods of Ring Resonators. in *Microwave Ring Circuits and Related Structures*, 2nd ed., Hoboken, NJ: John Wiley & Sons, 2004, Ch. 3, Sec. 3.9, pp. 81–84.

6. Sjebamo, N. M.; Khamoudi, B. H.; Abul-Kassem, A. S. Measurement of Dielectric Eonstant of Some Materials Using Planar Technology. *International Conference on Computer and Electrical Engineering* **Dec. 2009**, *2*, 352–356.

7. Yogi, R. A.; Gangal, S. A.; Aiyer, R. C.; Karekar, R. N. Microwave Ring Resonator as a Novel Bio-material Moisture Sensor. *Sensors and Actuators B: Chemical* **July 1998**, *50* (1), 38–44.

8. Dow Corning Corporation, "Dow Corning 3110, 3112, and 3120 RTV Rubbers," RTV-3110 datasheet, Ref. No. 80-3427A-01, June 2010.

9. Silicones, Inc., "P Series for Electronic Applications: Product Information," RTV-2 datasheet, www.silicones-inc.com.

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Appendix A. Calibrating the Agilent N9923A Vector Network Analyzer

To perform a two-port calibration of the N9923A unit, follow these steps:

(1) Locate the Open-Short-Load calibration standard for the N9923A, seen in figure A-1.

Figure A-1. Open-Short-Load N-male calibration standard for the Agilent N9923A.

(2) Power up the N9923A. Set the measurement to S_{21}, the desired frequency range, and the desired frequency resolution.

   a. Press “up-arrow”, then “Measure” (number 1). Select “S21”.

   b. Press “Freq/Dist”. Select “Start”. Enter the desired starting frequency.

   c. Press “Stop”. Enter the desired ending frequency.

   d. Press “up-arrow”, then “Sweep” (number 3). Select “Resolution”. Select the desired number of measurement points.

(3) Perform the mechanical calibration:

   a. Press “up-arrow”, then “Cal” (number 5).

   b. Select “Mechanical Cal”. Select “Start Calibration”.

   c. Follow the directions of the Cal Wizard.

      i. Connect the “Open” termination to Port 1. Select “Measure”.

      ii. Connect the “Short” termination to Port 1. Select “Measure”.

      iii. Connect the “Load” termination to Port 1. Select “Measure”.

iv. Connect Port 1 to Port 2 using the pair of 25-ft cables, N-to-SMA connectors, and SMA barrel. Select “Measure”.

v. Select “Finish”.

Appendix B. Depth of Dielectric Sample Required for Measurement

Since the electric fields of a microstrip line are confined near to the conductors, the ring resonator "sees" only the surface of the dielectric under test. Essentially, the ring-resonator technique measures the dielectric constant at the material's surface.

The absolute depth of material required to make an accurate measurement depends on the thickness of the resonator PCB and the frequency band of the measurement. Generally, the depth of sample required for the space above the ring to be sufficiently "filled" decreases as the thickness of the resonator PCB decreases and as the frequency of the measurement increases.

To generate a rule-of-thumb for the sample thickness required for an accurate measurement, the ring-resonator measurement was simulated using a sample of constant $Re\{\varepsilon_r\}$ but varied thickness on top of a ring printed in Rogers 4350B. The $|S_{21}|$ trace for the measurement is given in figure B-1.

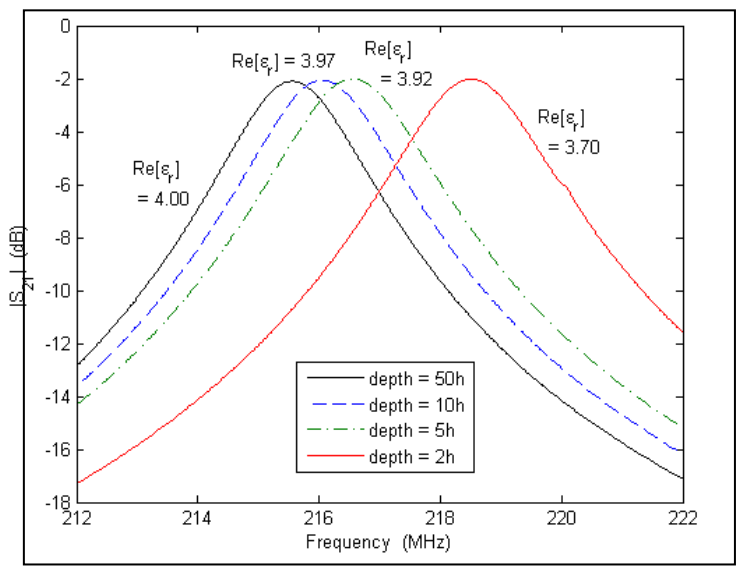

Figure B-1. Simulated permittivity calculation for different sample depths: PCB board height h = 20 mil, $Re\{\varepsilon_r\}$ for the PCB = 3.66, $\tan\delta$ for the PCB = 0.0031, "true" $Re\{\varepsilon_r\}$ for the sample = 4.00.

For a sample depth of 5h, the measured value of $Re\{\varepsilon_r\}$ is within 2% of the true value. For a sample depth of 10h, the measured value is within 1% of the true value. For a sample depth of 50h, the measured value is equal to the true value, rounding to the nearest hundredth of $Re\{\varepsilon_r\}$.

For the electric fields above the ring resonator to be completely confined to the dielectric sample and the PCB, the depth of the sample should be greater than or equal to 50h. For Rogers 4350B,

$$h_{\text{board}} = 20 \text{ mil} \qquad h_{\text{sample}} \geq 10 \cdot 20 \text{ mil}$$
$$h_{sample} \geq 200 \text{ mil} = \tfrac{1}{5} \text{ in} \,. \tag{B-1}$$

Appendix C. "N9923A_ringres" Script and Associated Functions

```
function varargout = N9923A_ringres_6GHz(varargin)

gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @N9923A_ringres_OpeningFcn, ...
                   'gui_OutputFcn',  @N9923A_ringres_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% executes before the GUI is made visible %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function N9923A_ringres_OpeningFcn(hObject, eventdata, handles, varargin)

handles.output = hObject;
guidata(hObject, handles);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% "Initialize the N9923A" button %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function pushbutton9_Callback(hObject, eventdata, handles)

% connect to the N9923A via TCP/IP:
%  set the sweep to continuous; set the measurement to S21;
%  set the format to log magnitude; set the power output to 0 dBm
global t;
t = tcpip('169.254.1.101',5025);
set(t,'InputBufferSize',1280000);
fopen(t);
fprintf(t,'INIT:CONT 1');
fprintf(t,'CALC:PAR:DEF S21');
fprintf(t,'CALC:FORM MLOG');
fprintf(t,'SOUR:POW 0');
fclose(t);

% set the lower frequency for the S21 traces
global start_frequency;
start_frequency = str2num(get(handles.MinFreq,'String'));

% set the upper frequency for the S21 traces
global end_frequency;
end_frequency = str2num(get(handles.MaxFreq,'String'));

% set the frequency resolution (in points) for the S21 traces
global points;
points = str2num(get(handles.Resolution,'String'));

% set the minimum power (in dBm) to be displayed by the N9923A
```

```
global pwr_min;
pwr_min = str2num(get(handles.MinPwr,'String'));

% set the maximum power (in dBm) to be displayed by the N9923A
global pwr_max;
pwr_max = str2num(get(handles.MaxPwr,'String'));

% initialize the 'sample absent' data with zeroes
global S21_dB_air;
S21_dB_air = zeros(1,points);

% initialize the 'sample present' data with zeroes
global S21_dB_sample;
S21_dB_sample = zeros(1,points);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% update the "Resolution (MHz)" value
span = end_frequency - start_frequency;
set(handles.ResolutionMHz,'String',num2str(span/(points-1)));
guidata(hObject,handles);

% connect to the N9923A via TCP/IP:
%  set the number of points; set the start and stop frequencies;
%  set the lower and upper display bounds on the power
fopen(t);
fprintf(t,['SWE:POIN ' num2str(points)]);
fprintf(t,['FREQ:STAR ' num2str(start_frequency) 'e6']);
fprintf(t,['FREQ:STOP ' num2str(end_frequency) 'e6']);
fprintf(t,['DISP:WIND:TRAC:Y:BOTT ' num2str(pwr_min)]);
fprintf(t,['DISP:WIND:TRAC:Y:TOP ' num2str(pwr_max)]);
fclose(t);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% "Acquire data from N9923A:  No sample" button %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function pushbutton2_Callback(hObject, eventdata, handles)

% set the lower frequency for the S21 traces
global start_frequency;
start_frequency = str2num(get(handles.MinFreq,'String'));

% set the upper frequency for the S21 traces
global end_frequency;
end_frequency = str2num(get(handles.MaxFreq,'String'));

% set the frequency resolution (in points) for the S21 traces
global points;
points = str2num(get(handles.Resolution,'String'));

% set the minimum power (in dBm) to be displayed by the N9923A
global pwr_min;
pwr_min = str2num(get(handles.MinPwr,'String'));

% set the maximum power (in dBm) to be displayed by the N9923A
global pwr_max;
pwr_max = str2num(get(handles.MaxPwr,'String'));

% update the "Resolution (MHz)" value
span = end_frequency - start_frequency;
set(handles.ResolutionMHz,'String',num2str(span/(points-1)));
guidata(hObject,handles);

% connect to the N9923A via TCP/IP:
%  set the number of points; set the start and stop frequencies;
%  set the lower and upper display bounds on the power
global t;
fopen(t);
fprintf(t,['SWE:POIN ' num2str(points)]);
```

```
fprintf(t,['FREQ:STAR ' num2str(start_frequency) 'e6']);
fprintf(t,['FREQ:STOP ' num2str(end_frequency) 'e6']);
fprintf(t,['DISP:WIND:TRAC:Y:BOTT ' num2str(pwr_min)]);
fprintf(t,['DISP:WIND:TRAC:Y:TOP ' num2str(pwr_max)]);

% pause for at least 1 sweep-length before reading data from the N9923A
pause(8 + 3.2/3000*points);

% grab data from the N9923A: read the raw data samples into a vector
fprintf(t,'TRACE:DATA? FDATA');
raw_data = fscanf(t);
fclose(t);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% set the 'sample absent' S21 trace equal to the raw data trace
global S21_dB_air S21_dB_sample;
S21_dB_air = str2num(raw_data);

% generate the corresponding vector of frequency points
global frequency start_frequency end_frequency points;
span = end_frequency - start_frequency;
delta_f = span / (points - 1);
frequency = (start_frequency:delta_f:end_frequency);

% if the lengths of the 'sample absent' and 'sample present' traces do not match,
%  set the 'sample present' trace to zero
if ( length(S21_dB_sample) ~= length(S21_dB_air) )
    S21_dB_sample = zeros(1,length(S21_dB_air));
end

% plot the current 'sample absent' and 'sample present' traces in the upper window
global pwr_min pwr_max;
axes(handles.NA_trace)
plot(frequency,S21_dB_air,'b',...
     frequency,S21_dB_sample,'r')
axis([start_frequency end_frequency pwr_min pwr_max])
ylabel('|S_{21}| (dB)')
xlabel('Frequency  (MHz)')


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% "Acquire data from N9923A:  Sample" button %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function pushbutton3_Callback(hObject, eventdata, handles)

% set the lower frequency for the S21 traces
global start_frequency;
start_frequency = str2num(get(handles.MinFreq,'String'));

% set the upper frequency for the S21 traces
global end_frequency;
end_frequency = str2num(get(handles.MaxFreq,'String'));

% set the frequency resolution (in points) for the S21 traces
global points;
points = str2num(get(handles.Resolution,'String'));

% set the minimum power (in dBm) to be displayed by the N9923A
global pwr_min;
pwr_min = str2num(get(handles.MinPwr,'String'));

% set the maximum power (in dBm) to be displayed by the N9923A
global pwr_max;
pwr_max = str2num(get(handles.MaxPwr,'String'));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% update the "Resolution (MHz)" value
span = end_frequency - start_frequency;
```

```
set(handles.ResolutionMHz,'String',num2str(span/(points-1)));
guidata(hObject,handles);

% connect to the N9923A via TCP/IP:
%  set the number of points; set the start and stop frequencies;
%  set the lower and upper display bounds on the power
global t;
fopen(t);
fprintf(t,['SWE:POIN ' num2str(points)]);
fprintf(t,['FREQ:STAR ' num2str(start_frequency) 'e6']);
fprintf(t,['FREQ:STOP ' num2str(end_frequency) 'e6']);
fprintf(t,['DISP:WIND:TRAC:Y:BOTT ' num2str(pwr_min)]);
fprintf(t,['DISP:WIND:TRAC:Y:TOP ' num2str(pwr_max)]);

% pause for at least 1 sweep-length before reading data from the N9923A
pause(8 + 3.2/3000*points);

% grab data from the N9923A: read the raw data samples into a vector
fprintf(t,'TRACE:DATA? FDATA');
raw_data = fscanf(t);
fclose(t);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% set the 'sample present' S21 trace equal to the raw data trace
global S21_dB_air S21_dB_sample;
S21_dB_sample = str2num(raw_data);

% generate the corresponding vector of frequency points
global frequency start_frequency end_frequency points;
span = end_frequency - start_frequency;
delta_f = span / (points - 1);
frequency = (start_frequency:delta_f:end_frequency);

% if the lengths of the 'sample absent' and 'sample present' traces do not match,
%  set the 'sample absent' trace to zero
if ( length(S21_dB_sample) ~= length(S21_dB_air) )
    S21_dB_air = zeros(1,length(S21_dB_sample));
end

% plot the current 'sample absent' and 'sample present' traces in the upper window
global pwr_min pwr_max;
axes(handles.NA_trace)
plot(frequency,S21_dB_air,'b',...
     frequency,S21_dB_sample,'r')
axis([start_frequency end_frequency pwr_min pwr_max])
ylabel('|S_{21}| (dB)')
xlabel('Frequency  (MHz)')


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% "Calculate dielectric constant:  Single point" button %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function pushbutton4_Callback(hObject, eventdata, handles)

% read the value for "Harmonic"
global harmonic;
switch get(handles.Harmonic,'Value')
    case 1
        harmonic = 1;
    case 2
        harmonic = 2;
    case 3
        harmonic = 3;
    case 4
        harmonic = 4;
    case 5
        harmonic = 5;
    case 6
        harmonic = 6;
```

```
    otherwise
        harmonic = 1;
end

% read the value for "Ring Frequency (MHz)", the nominal design frequency
global ring_frequency;
switch get(handles.RingFrequency,'Value')
    case 1
        ring_frequency = 250;
    case 2
        ring_frequency = 300;
    case 3
        ring_frequency = 350;
    case 4
        ring_frequency = 400;
    case 5
        ring_frequency = 550;
    case 6
        ring_frequency = 900;
    case 7
        ring_frequency = 1200;
    case 8
        ring_frequency = 1300;
    case 9
        ring_frequency = 1400;
    case 10
        ring_frequency = 1500;
    case 11
        ring_frequency = 2000;
    otherwise
        ring_frequency = 250;
end

global frequency S21_dB_air S21_dB_sample start_frequency;

% determine the lowest resonant frequency of the ring for 'sample absent' case;
%  set the lower and upper bounds of the curve fit to 0.5x and 1.5x this frequency
[value,index] = min(abs(frequency - ring_frequency * 1.1));
[value,index] = max(S21_dB_air(1:index));
freq_fundamental_air = frequency(index);

[value,index_1] = min(abs(frequency - freq_fundamental_air*(harmonic - 0.5)));
[value,index_2] = min(abs(frequency - freq_fundamental_air*(harmonic + 0.5)));

% determine the lowest resonant frequency of the ring for 'sample present' case;
%  set the lower and upper bounds of the curve fit to 0.5x and 1.5x this frequency
[value,index] = min(abs(frequency - ring_frequency * 1.1));
[value,index] = max(S21_dB_sample(1:index));
freq_fundamental_sample = frequency(index);

[value,index_3] = min(abs(frequency - freq_fundamental_sample*(harmonic - 0.5)));
[value,index_4] = min(abs(frequency - freq_fundamental_sample*(harmonic + 0.5)));

% fit the two S21 traces to a Laurentzian curve:
%  solve for the true resonant frequency, quality factor, and the fitted S21
[ f0, Q0, S_21_0 ] = laurentzian( frequency(index_1:index_2),S21_dB_air(index_1:index_2) );
[ f1, Q1, S_21_1 ] = laurentzian( frequency(index_3:index_4),S21_dB_sample(index_3:index_4) );

% plot the recorded and fitted S21 traces
global pwr_min pwr_max;
axes(handles.NA_trace_cut)
plot(frequency(index_1:index_2),S21_dB_air(index_1:index_2),'bo',...
     frequency(index_1:index_2),S_21_0,'k-',...
     frequency(index_3:index_4),S21_dB_sample(index_3:index_4),'ro',...
     frequency(index_3:index_4),S_21_1,'k-','MarkerSize',1.5)
axis([frequency(index_3) frequency(index_2) pwr_min pwr_max])
ylabel('|S_{21}| (dB)')
xlabel('Frequency  (MHz)')

% solve for dielectric constant using lookup curves from FEKO;
%  multiply the loss tangent by the real part to obtain the imaginary part
```

```
[epsilon_real,loss_tangent] = eps_lookup(ring_frequency,harmonic,f0,Q0,f1,Q1);
epsilon_imag = -epsilon_real * loss_tangent;

% update the "Nominal Frequency", "Real Part", and "Imaginary Part" values displayed
set(handles.RealPart,'String',num2str(epsilon_real));
set(handles.ImaginaryPart,'String',num2str(epsilon_imag));
set(handles.FreqOperation,'String',[num2str(ring_frequency*harmonic) ' MHz']);
guidata(hObject,handles);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% "Calculate dielectric constant:  Multiple harmonics" button %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function pushbutton5_Callback(hObject, eventdata, handles)

% read the value for "Harmonic"
global harmonics;
switch get(handles.Harmonics,'Value')
    case 1
        harmonics = 1;
    case 2
        harmonics = (1:2);
    case 3
        harmonics = (1:3);
    case 4
        harmonics = (1:4);
    case 5
        harmonics = (1:5);
    case 6
        harmonics = (1:6);
    otherwise
        harmonics = (1:3);
end

% read the value for "Ring Frequency (MHz)", the nominal design frequency
global ring_frequency;
switch get(handles.RingFrequency,'Value')
    case 1
        ring_frequency = 250;
    case 2
        ring_frequency = 300;
    case 3
        ring_frequency = 350;
    case 4
        ring_frequency = 400;
    case 5
        ring_frequency = 550;
    case 6
        ring_frequency = 900;
    case 7
        ring_frequency = 1200;
    case 8
        ring_frequency = 1300;
    case 9
        ring_frequency = 1400;
    case 10
        ring_frequency = 1500;
    case 11
        ring_frequency = 2000;
    otherwise
        ring_frequency = 250;
end

global frequency S21_dB_air S21_dB_sample start_frequency;

% determine the lowest resonant frequency of the ring for 'sample absent' case;
[value,index] = min(abs(frequency - ring_frequency * 1.1));
[value,index] = max(S21_dB_air(1:index));
freq_fundamental_air = frequency(index);
```

```
% determine the lowest resonant frequency of the ring for 'sample present' case;
[value,index] = min(abs(frequency - ring_frequency * 1.1));
[value,index] = max(S21_dB_sample(1:index));
freq_fundamental_sample = frequency(index);

%  set the lower and upper bounds of each harmonic 'cut';
%   fit each pair of S21 traces to a Laurentzian curve:  find f0, f1, Q0, Q1
%   solve for dielectric constant using lookup curves from FEKO;
%   multiply the loss tangent by the real part to obtain the imaginary part
for counter = 1:length(harmonics)
    [value,index_1] = min(abs(frequency - freq_fundamental_air*(harmonics(counter) - 0.5)));
    [value,index_2] = min(abs(frequency - freq_fundamental_air*(harmonics(counter) + 0.5)));

    [value,index_3] = min(abs(frequency - freq_fundamental_sample*(harmonics(counter) - 0.5)));
    [value,index_4] = min(abs(frequency - freq_fundamental_sample*(harmonics(counter) + 0.5)));

    [ f0, Q0, S_21_0 ] = laurentzian( frequency(index_1:index_2),S21_dB_air(index_1:index_2) );
    [ f1, Q1, S_21_1 ] = laurentzian( frequency(index_3:index_4),S21_dB_sample(index_3:index_4)
);

    [eps_real(counter),loss_tan(counter)] =
eps_lookup(ring_frequency,harmonics(counter),f0,Q0,f1,Q1);
    eps_imag(counter) = -eps_real(counter) * loss_tan(counter);
end

% find the average values for the real & imaginary parts over this set of harmonics
mean_eps_real = mean(eps_real);
mean_eps_imag = mean(eps_imag);

% generate a vector of frequency points for the chosen harmonics
freq_pts = ring_frequency * harmonics;

% open a new figure window:  2x1;
%  plot the real & imaginary parts for the chosen harmonics
figure(1)
subplot(2,1,1)
plot( freq_pts, eps_real, 'ko')
axis([ring_frequency*.5 ring_frequency*(counter+.5) 1 max(eps_real)*1.1])
ylabel('{\bfRe[ \epsilon_r ]}  (real part)')
text(mean(freq_pts),1+.2*max(eps_real)*1.1,['avg = ' num2str(mean_eps_real)])
title('Dielectric Constant:  Multiple Harmonics')
subplot(2,1,2)
plot( freq_pts, -eps_imag, 'ko')
axis([ring_frequency*.5 ring_frequency*(counter+.5) 0 max(-eps_imag)*1.1])
ylabel('{\bf-Im[ \epsilon_r ]}  (imaginary part)')
text(mean(freq_pts),.2*max(-eps_imag)*1.1,['avg = ' num2str(-mean_eps_imag)])
xlabel('Frequency  (MHz)')

% if "Save file?" is checked, save the real & imaginary parts to "[filename].mat"
if ( get(handles.checkbox1,'Value') )
    save( get(handles.edit8,'String'), 'freq_pts', 'eps_real', 'eps_imag' );
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% "Load S2P file:  No sample" button %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function LoadFileNoSample_Callback(hObject, eventdata, handles)

global S21_dB_air S21_dB_sample
global frequency start_frequency end_frequency points;

% import the S21 data for the 'sample absent' case from an S2P file:
%  the frequency vector is the 1st column; the S21 magnitude data is the 4th column
[filename_nosample, pathname_nosample, FI_nosample] = uigetfile('*.s2p', 'Open File:  No
Sample');
data_nosample = importdata([pathname_nosample '\' filename_nosample]);
frequency = data_nosample.data(:,1)'/10^6;
points = length(frequency);
S21_dB_air = data_nosample.data(:,4)';
```

```
start_frequency = frequency(1);
end_frequency = frequency(length(frequency));

% if the lengths of the 'sample absent' and 'sample present' traces do not match,
%  set the 'sample present' trace to zero
if ( length(S21_dB_sample) ~= length(S21_dB_air) )
    S21_dB_sample = zeros(1,length(S21_dB_air));
end

% plot the current 'sample absent' and 'sample present' traces in the upper window
axes(handles.NA_trace)
plot(frequency,S21_dB_air,'b',...
     frequency,S21_dB_sample,'r')
axis([start_frequency end_frequency min(S21_dB_air)-10 max(S21_dB_air)+10])
ylabel('|S_{21}| (dB)')
xlabel('Frequency  (MHz)')


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% "Load S2P file:  Sample" button %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function LoadFileSample_Callback(hObject, eventdata, handles)

global S21_dB_air S21_dB_sample
global frequency start_frequency end_frequency points;

% import the S21 data for the 'sample present' case from an S2P file:
%  the frequency vector is the 1st column; the S21 magnitude data is the 4th column
[filename_sample, pathname_sample, FI_sample] = uigetfile('*.s2p', 'Open File:  Sample');
data_sample = importdata([pathname_sample '\' filename_sample]);
frequency = data_sample.data(:,1)'/10^6;
points = length(frequency);
S21_dB_sample = data_sample.data(:,4)';

start_frequency = frequency(1);
end_frequency = frequency(length(frequency));

% if the lengths of the 'sample absent' and 'sample present' traces do not match,
%  set the 'sample absent' trace to zero
if ( length(S21_dB_sample) ~= length(S21_dB_air) )
    S21_dB_air = zeros(1,length(S21_dB_sample));
end

% plot the current 'sample absent' and 'sample present' traces in the upper window
axes(handles.NA_trace)
plot(frequency,S21_dB_air,'b',...
     frequency,S21_dB_sample,'r')
axis([start_frequency end_frequency min(S21_dB_air)-10 max(S21_dB_air)+10])
ylabel('|S_{21}| (dB)')
xlabel('Frequency  (MHz)')
```

```
function [epsilon_real,loss_tangent] =
eps_lookup(freq_ring,harmonic,f_unloaded,q_unloaded,f_loaded,q_loaded)

% This function returns measured permittivity (real) and loss tangent
%  for a ring-resonator measurement:
%
%    'freq_ring' = nominal resonant frequency of ring (MHz)
%    'harmonic' = harmonic of resonant frequency (1,2,3,...)
%    'f_unloaded' = resonant frequency of ring without sample, measured (MHz)
%    'q_unloaded' = quality factor of ring without sample, measured
%    'f_loaded' = resonant frequency of ring with sample, measured (MHz)
%    'q_loaded' = quality factor of ring with sample, measured
%
%    'epsilon_real' = relative permittivity of sample, real part
%    'loss_tangent' = loss tangent of sample

% A limited subset of ring frequencies and harmonics have been simulated in
%  FEKO to generate lookup curves for real & imaginary dielectric constants.
% For those combinations of frequencies and harmonics outside this subset...
%  if the harmonic chosen is greater than 4, set the harmonic value to 4;
%  if the ring frequency chosen is above 550 MHz, set the harmonic to 1;
%  if the ring frequency chosen is 900 MHz, set the ring frequency to 1200 MHz
if (harmonic > 4)
    harmonic = 4;
end
if (freq_ring > 550)
    harmonic = 1;
end
if (freq_ring == 900)
    freq_ring = 1200;
end

% load the FEKO lookup curves appropriate for calculating the dielectric constant
load(['ring_' num2str(freq_ring) 'MHz_harmonic' num2str(harmonic)]);

% find the index for the real part nearest the calculated f1/f0
[value,index] = min(abs(f_loaded/f_unloaded - f1_f0));

% interpolate along the lookup curves to determine the real & imaginary parts
if (f_loaded/f_unloaded == f1_f0(index))
    epsilon_real = e_real(index);
    loss_slope = k(index);
    q_lossless = q_u(index);
else
    if ( f_loaded/f_unloaded < f1_f0(index) );
        f_1 = f1_f0(index + 1);
        e_1 = e_real(index + 1);
        k_1 = k(index + 1);
        q_1 = q_u(index + 1);
        f_2 = f1_f0(index);
        e_2 = e_real(index);
        k_2 = k(index);
        q_2 = q_u(index);
    else
        f_1 = f1_f0(index);
        e_1 = e_real(index);
        k_1 = k(index);
        q_1 = q_u(index);
        f_2 = f1_f0(index - 1);
        e_2 = e_real(index - 1);
        k_2 = k(index - 1);
        q_2 = q_u(index - 1);
    end

    m_a = (e_2 - e_1) / (f_2 - f_1);
    m_b = (k_2 - k_1) / (e_2 - e_1);
    m_c = (q_2 - q_1) / (e_2 - e_1);

    epsilon_real = m_a * (f_loaded/f_unloaded - f_1) + e_1;
    loss_slope = m_b * (epsilon_real - e_1) + k_1;
    q_lossless = m_c * (epsilon_real - e_1) + q_1;
```

```
end

loss_tangent = loss_slope * (1/q_loaded - 1/q_unloaded);

% loss tangent cannot be less than zero
if ( loss_tangent < 0 )
    loss_tangent = 0;
end




function [ f0_fit, Q_fit, S_21_dB_fit ] = laurentzian( freq, S_21_dB )

% This function performs a Laurentzian curve fit on an (x,y) data set:
%
%    'freq' = vector of frequency points (Hz), the 'x' values
%    'S_21_dB' = vector of data points (dB magnitude), the 'y' values
%
%    'f0_fit' = resonant frequency extracted from the curve fit (Hz)
%    'Q_fit' = quality factor extracted from the curve fit
%    'S_21_dB_fit' = vector of points for the curve fit


% convert dB magnitude into absolute magnitude
S_21_abs = 10.^(S_21_dB/20);


% make initial guesses for the amplitude and resonant frequency of the fit:
%  the amplitude is intially set to the maximum value of the data set;
%  the resonant frequency is set to correspond with this maximum value
[A_guess,index] = max(S_21_dB);
f0_guess = freq(index);


% make an initial guess for the quality factor of the fit:
%  find the 3-dB-down points on either side of the (initial) resonant frequency;
%  set the quality factor to 1/ the difference of these two frequency points
dB_down = 3;
index_lower = 1;
freq_lower = freq(index_lower);

for m = 1:index
    if ( S_21_dB(m) - A_guess < -dB_down )
        freq_lower = freq(m);
        index_lower = m;
    end
end

index_upper = length(freq);
freq_upper = freq(index_upper);

for n = index:length(freq)
    if ( S_21_dB(n) - A_guess > -dB_down )
        freq_upper = freq(n);
        index_upper = n;
    end
end

Q_guess = f0_guess / (freq_upper - freq_lower);


% for different combinations of quality factor, resonant frequency, and amplitude,
%  compute the absolute difference between the curve fit and the data trace,
%  and generate a 3-dimensional matrix of error values for each combination
Q = (.6:.02:1.2)*Q_guess;
f0 = (.99:.01:1.01)*f0_guess;
A = A_guess-1:.01:A_guess+1;

error = zeros(length(Q),length(f0),length(A));
```

```
for m = 1:length(Q)
    for n = 1:length(f0)
        for p = 1:length(A)
            S21 = 10^(A(p)/20) ./ sqrt(1 + 4*(Q(m))^2*(freq / f0(n) - 1).^2);

            error(m,n,p) = sum((S_21_abs - S21).^2);
        end
    end
end


% find the minimum value within the error matrix;
%  the 3 indices corresponding to this minimum are the fitted values for
%  amplitude, resonant frequency, and quality factor for the data set
[value,index_1] = min(error);
[value,index_2] = min(min(error));
[value,index_3] = min(min(min(error)));

p_fit = index_3;
n_fit = index_2(1,1,p_fit);
m_fit = index_1(1,n_fit,p_fit);

A_fit = A(p_fit);
f0_fit = f0(n_fit);
Q_fit = Q(m_fit);

% generate the full fitted Laurentian curve for the data set
S_21_dB_fit = 20*log10( 10^(A_fit/20) ./ sqrt(1 + 4*Q_fit^2*(freq / f0_fit - 1).^2));
```

List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
EM	electromagnetic
GPR	ground-penetrating radar
GUI	graphical user interface
LAN	local area network
PCB	printed-circuit-board
RF	radio frequency
RTV	real-time-vulcanizing
USB	Universal Serial Bus
UWB	ultra wideband
VNA	vector network analyzer

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TOTAL: 12 (1 ELEC, 11 HCS)

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