Supporting Information for:

Non-Resonant Transmission Line Probe for Sensitive Interferometric Electron Spin Resonance Detection

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Transmission Line Equations

The width of the signal line on the mircrostrip shown in figure s1 is calculated using the following equations [1, 2],

$$Z_0 = \sqrt{\frac{\mu_0 \varepsilon_0}{\varepsilon_e}}\ \frac{1}{C_a}\ ohms$$

$$C_a = \begin{cases} \dfrac{2\pi\varepsilon_0}{ln\left({}^{8h}/_{w} + {}^{w}/_{4h}\right)} & when\ \dfrac{w}{h} \leq 1 \\ \varepsilon_0\left[\dfrac{w}{h} + 1.393 + 0.667ln\left(\dfrac{w}{h} + 1.44\right)\right] & when\ \dfrac{w}{h} > 1 \end{cases}$$

$$\varepsilon_r = \frac{\varepsilon_r - 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{w}\right)^{-1/2} + F - 0.217(\varepsilon_r - 1)\frac{T}{\sqrt{wh}}$$

$$F = \begin{cases} 0.02(\varepsilon_r - 1)\left(1 - \dfrac{w}{h}\right)^2 & when\ \dfrac{w}{h} < 1 \\ 0 & when\ \dfrac{w}{h} > 1 \end{cases}$$

$When\ 0.1 < {}^{w}/_{h} < 2.0\ and\ 1 < \varepsilon_r < 15$

$$Z_0 \approx \frac{87}{\sqrt{\varepsilon_r + 1.41}} ln\left(\frac{5.98h}{0.8w + T}\right)\ ohms$$

$\varepsilon_r = Dielectric\ constant$

$Z_0 = Characteristic\ impedance$

$\varepsilon_0 = \ Vacuum\ permitivity$

$\mu_0 = Vacuum\ permeability$

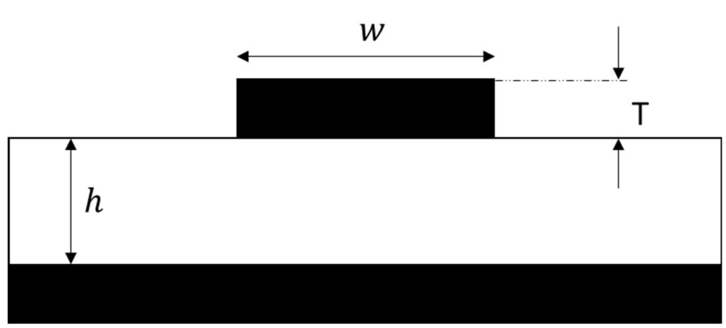
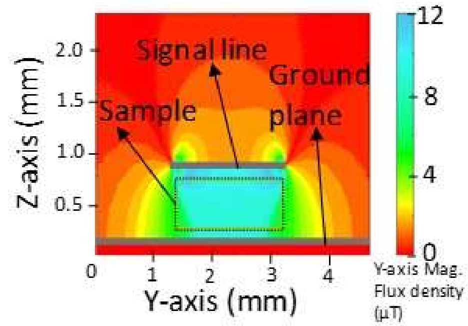
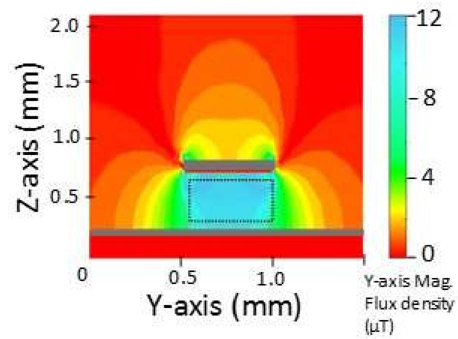
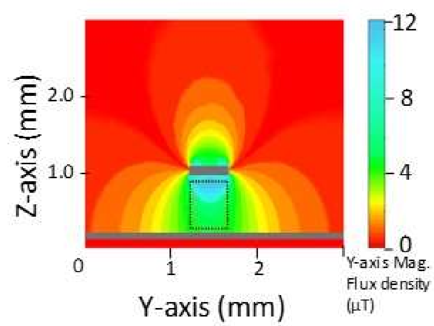
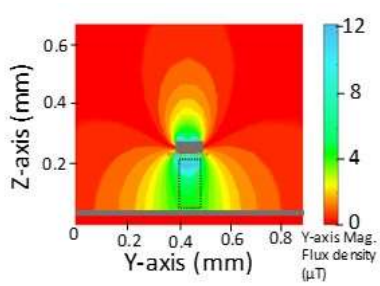


Figure S1: Geometry of the transmission line used for the given equations above.

Results of finite element simulation done for various transmission line geometries

dielectric thickness (mm)	dielectric constant	signal line width (mm)	Metal thickness (mm)	Area (mm^2)	Comsol
0.76	2	1.92	0.03556	0.96	
0.2	2	0.473	0.0355	0.07	
0.7	15	0.466	0.0355	0.233	
0.2	15	0.1	0.0355	0.015	

Time delay in a transmission line [1].

$$TD = \frac{x\sqrt{\varepsilon_r}}{c}$$

$c = \ speed\ of\ light\ in\ vacuum\ (3\ \times\ 10^8\ m/s)$

$x = length\ of\ transmission\ line\ in\ m$

$\varepsilon_r = Dielectric\ constant$

$TD = Timem\ Delay$

Components used in the ESR setup

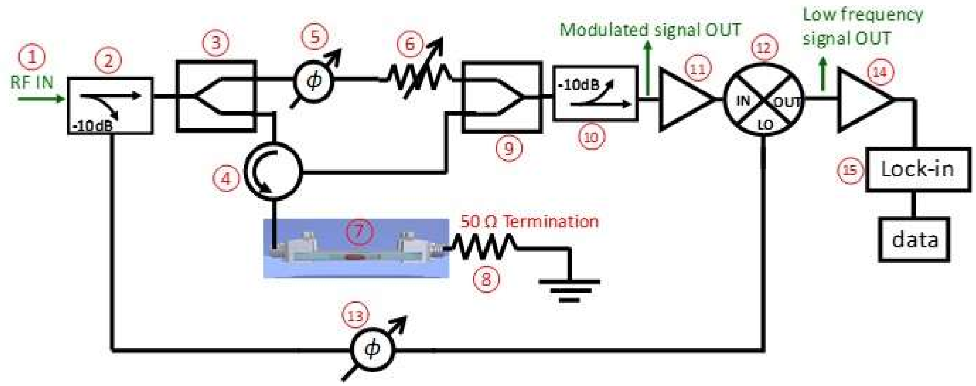


Figure S2: Complete setup for ESR measurement.

List of details of the components shown in Figure S2[1].

Number	Component Detail	Number	Component Detail	Number	Component Detail
1	Keysight E8257D, High Power Signal Generator opt. 521, 10 MHz to 20 GHz	7	Transmission line discussed in paper	13	Response microwave phase shifter DC-20 GHz, 53 deg/GHz*
2	MECA 10 db directional coupler 780-10-9.700, 50 Watts, 7.000-12.400 GHz	8	Fairview microwave 50 Ω termination DC-18GHZ, 1 watt Not required for transmission mode	14	North Hills wide band transformer, ratio 1:5, FSCM 98821
3	Meca 802-2-9.700 3 db Power divider/combiner	9	Meca 802-2-9.700 3 db Power divider/combiner	15	Standford SR830 Lock-in
4	8.4 GHz-9.7 GHz UTE microwave circulator Not required for transmission mode	10	MECA 10 db directional coupler 780-10-9.700, 50 Watts, 7.000-12.400 GHz		
5	Response microwave phase shifter DC-20 GHz, 53 deg/GHz	11	Miteq low noise amp. gain 50 db AFS43-08501160-09-10P-44		
6	50CA12.4-20 Alan Industries, 20 db, 8-12.4 GHz*	12	Miteq DMO812LW2 Mixer		

* Passive components rather than voltage-controlled components are preferred and used to avoid loss in signal integrity due to high VSWR (Voltage Standing Wave Ratio) in the latter.

[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the NIST nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Sample holders for liquid samples

The sample holder for liquid sample is designed as shown below. The channel is carved in the center layer. It is then sealed with the top and bottom layer with two openings such that liquid can be pipetted in and out of the channel. In principle, this simple liquid cell can easily be modified to include more complicated solution mixing stages.

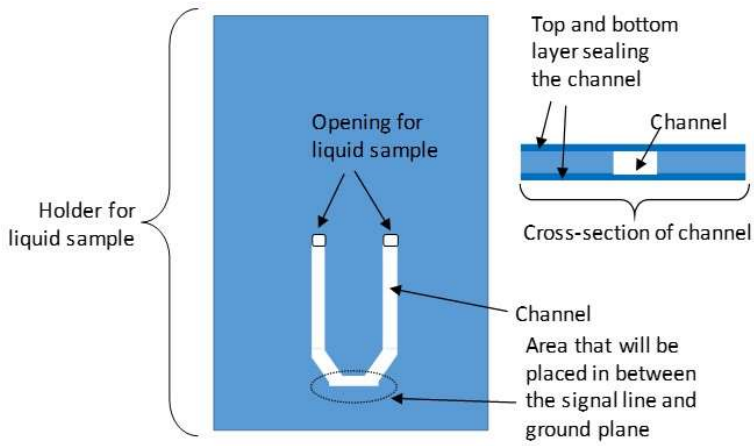


Figure S3: Schematic of a sample holder used for liquid sample.

Sample holder design for a mixing flow-cell.

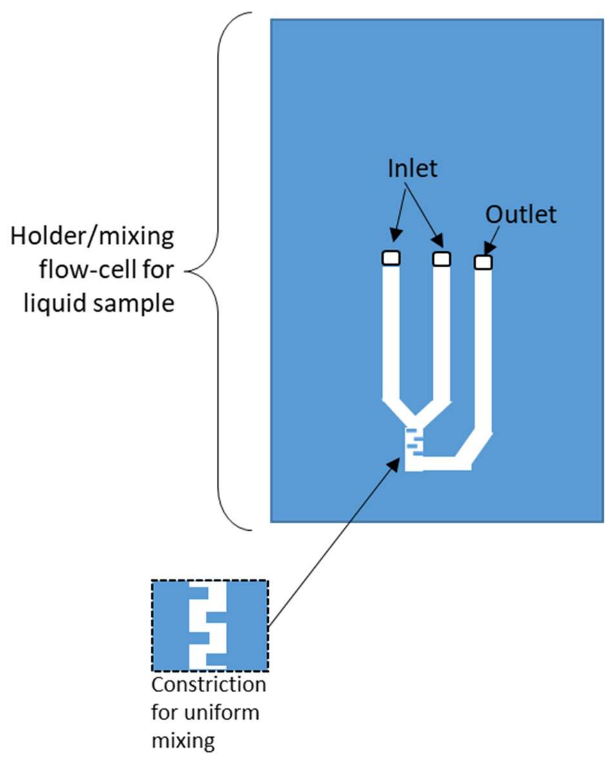


Figure S4: Schematic of a mixing flow-cell on the sample holder, with two inlets and one outlet.

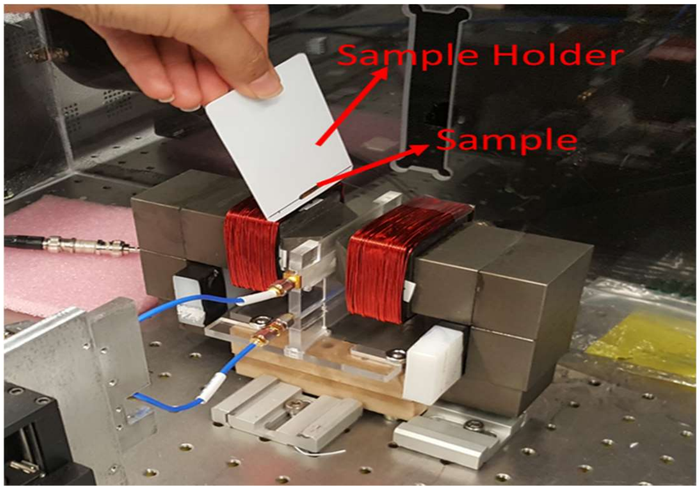


Figure S5: Picture of magnet and transmission line setup where the sample holder is shuttled in and out of the transmission line.

Limitations

As mentioned in the text, the available B1/input microwave power is somewhat limited. This is due to the power handling of the components in the interferometer circuit as well as the chosen geometry of the transmission line probe. For transmission line designs which accommodate thicker samples (larger dielectric thickness), there is a B1 penalty. For designs which accommodate thinner samples (smaller dielectric thickness), there is a potential for a sample volume penalty. As discussed above, the traveling wave nature of the transmission line probe does not restrict sample volume in the X-direction (see figure 1). However, the X-direction is practically limited by B0 uniformity. This can effectively limit the sample volume which can be probed. Also, we again note that the transmission line probe design is dependent on the sample composition (dielectric constant). Thus, if one were measuring a variety of samples with widely varying dielectric constants, several different transmission line probes would need to be used. Lastly, we note that sample misalignment is only a secondary concern. If the sample holder is misaligned or the transmission line probe tolerances result in a loose-fitting sample holder, the sensitivity can be regained by retuning of the interferometer circuit the desired level. If one keeps the interferometric cancellation (monitored by the output power) fixed, then small sample misalignments become unimportant.

References

[1] S. H. Hall, G. W. Hall, and J. A. McCall, *High speed digital system design : a handbook of interconnect theory and design practices*, New York: Wiley, 2000.

[2] M. V. Schneider, "Microstrip Lines for Microwave Integrated Circuits," *Bell System Technical Journal,* vol. 48, no. 5, pp. 1421-+, 1969.