This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2022-9615C

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Investigation of High-Resolution EMI Source Localization Using Near Field Measurements

*Kara Maurer[1], C. D. Nordquist [2], and J. T. Bernhard [1]

(1) Electromagnetics Laboratory, University of Illinois at Urbana-Champaign
(2) Sandia National Laboratories

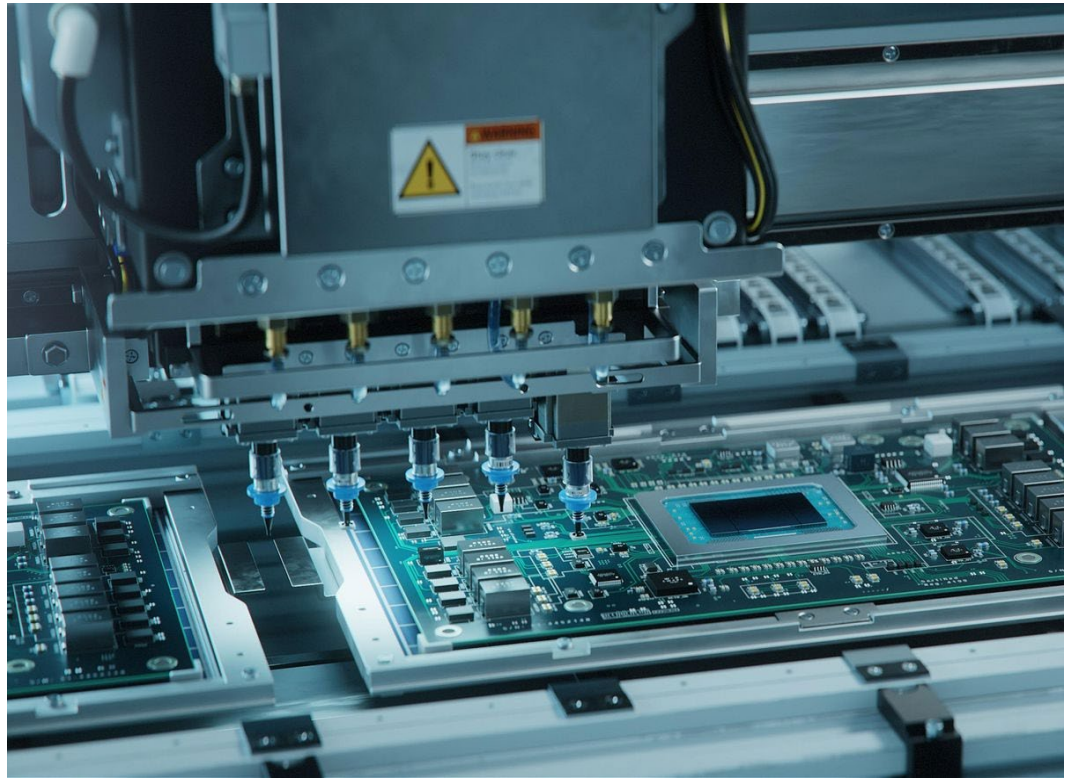
JULY 11, 2022

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Overview

- Motivation
  - Current state of EMI testing
- Discussion of characteristics of interest
- Existing methodologies
  - Commercial products
  - Published research
- Operational tradeoffs
- Preliminary investigation of shielded resonant loops



High density PCB [1]

[1] Pepitone, J. (2022, April 21). *5 ways the chip shortage is rewiring tech*. IEEE Spectrum. Retrieved June 29, 2022, from https://spectrum.ieee.org/chip-shortage-rewiring-tech

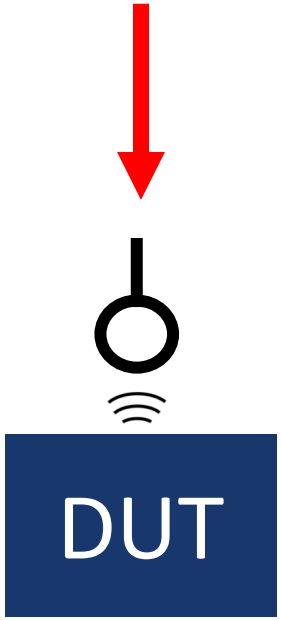
Motivation

Typical EMI testing is done in far-field

- Necessary for products to meet safety standards
- Not ideal for product development
- Would require pinpoint accuracy from an array to achieve desired resolution

Near-field can provide more information

- Increased accuracy and reliability
- Higher resolution capacity from higher proximity
- Better estimation of currents and EMI source locations
- Increasing module density requires higher resolution
- Low SNR, weak signal strength



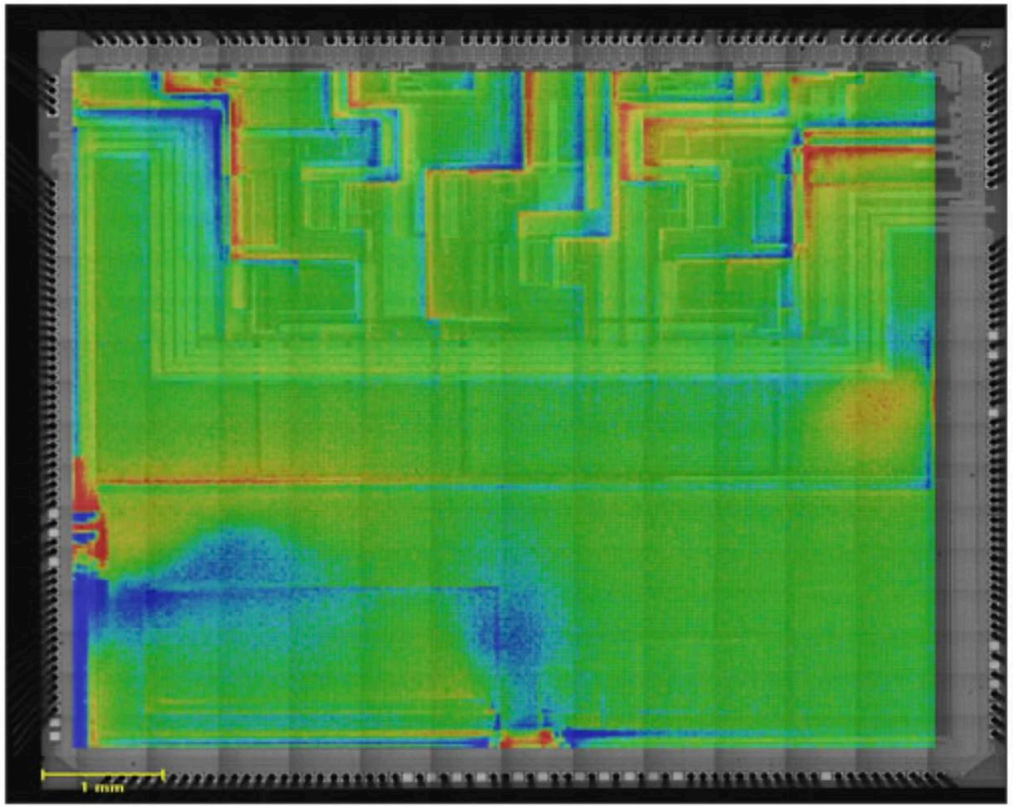
Motivation

Mapping probes lack combination of

- High resolution
- High sensitivity
- Small probe size
- Large bandwidth

Investigation serves to find the tradeoff between these four characteristics

- What sacrifices can be made
- What should be prioritized



Example near field magnetic field map from MicroMagnetics Circuit Scan [2]

[2] *CircuitScan 1000*. Micro Magnetics Sensible Solutions. (n.d.). Retrieved June 24, 2022, from https://www.micromagnetics.com/products_circuit_scan.html

Discussion of characteristics of interest

In order of priority:

1. High Resolution
   - 10 μm at minimum
   - Provides localization information even in dense modules
2. Large Bandwidth
   - 0.1 - 3.5 GHz
   - Lower and higher frequencies necessary for edge detection
3. High Sensitivity
   - Transient currents on the order of a tenth of mA
4. Small Probe Size
   - Less than 4 cm^3
   - Directly related to high resolution and desirable for the design

Existing methodologies

Micro Magnetics Circuit Scan “CS 1000” Specifications of Interest

- Complex Design
  - Contains 2 sensor types
    - Magnetic Tunnel Junction
      - Higher Sensitivity (μA level)
    - Giant Magnetoresistive
      - Higher Resolution (down to 100 nm)
- Drawbacks
  - Can be slow at high resolution
  - Small bandwidth (0 - 100 kHz)

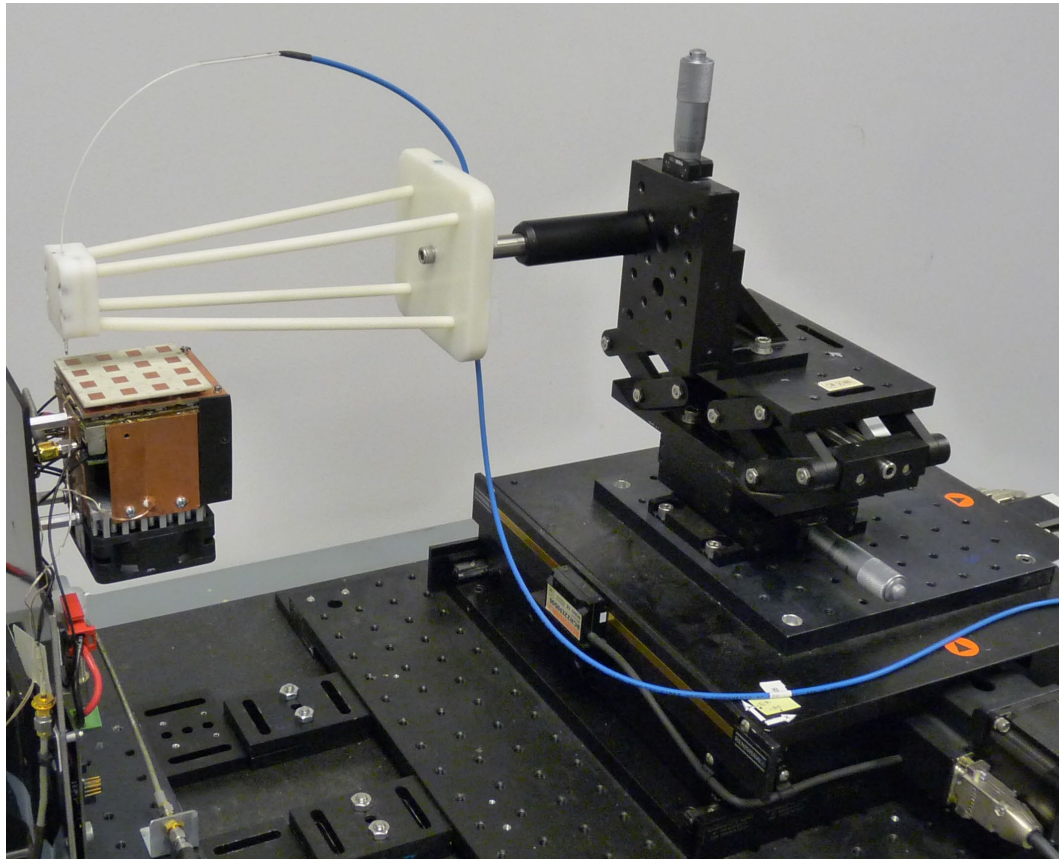
Circuit Scan System [2]

[2] *CircuitScan 1000*. Micro Magnetics Sensible Solutions. (n.d.). Retrieved June 24, 2022, from https://www.micromagnetics.com/products_circuit_scan.html

Existing methodologies

EMAG Technologies NeoScan Specifications of Interest

- Uses Optical Probe
  - Miniaturized optical crystal tips
- Large Bandwidth
  - 20 MHz – 20 GHz
- High Resolution
  - Down to 10 μm
- Needs high precision positioner



NeoScan probe in use [3]

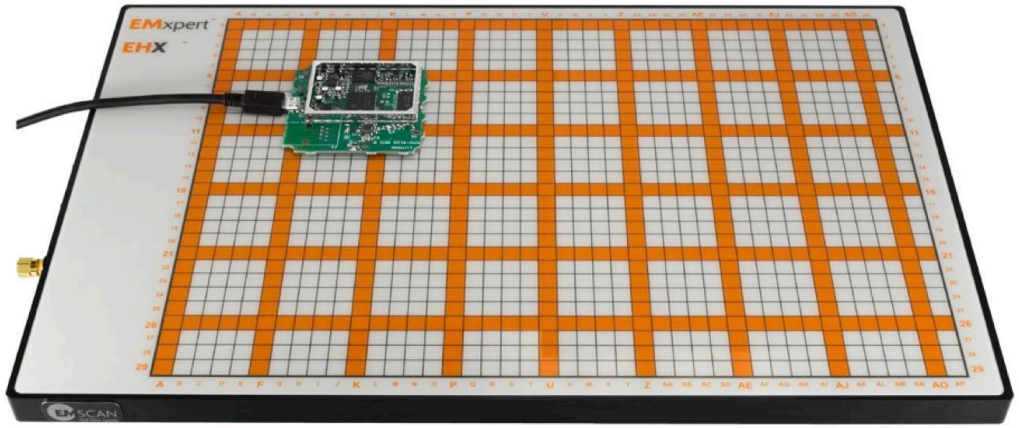
[3] *Electric field measurement system: EMAG Technologies Inc.*. EMAG Technologies Inc. | Innovative RF Solutions. (2019, May 8). Retrieved June 24, 2022, from https://emagtech.com/neoscan-system/

Existing methodologies

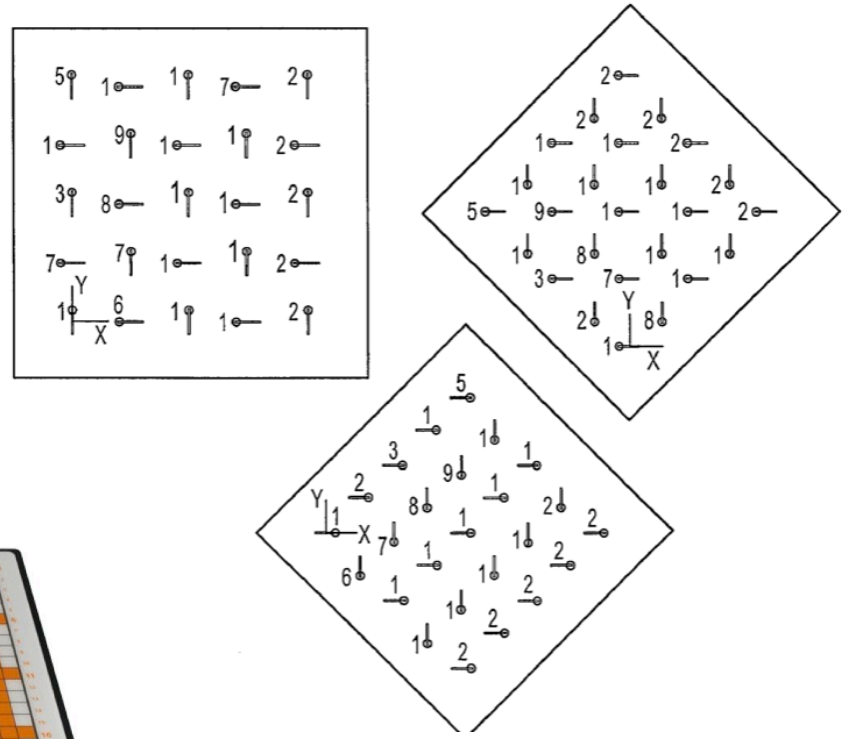
ERX+ Scanner

Specifications of Interest

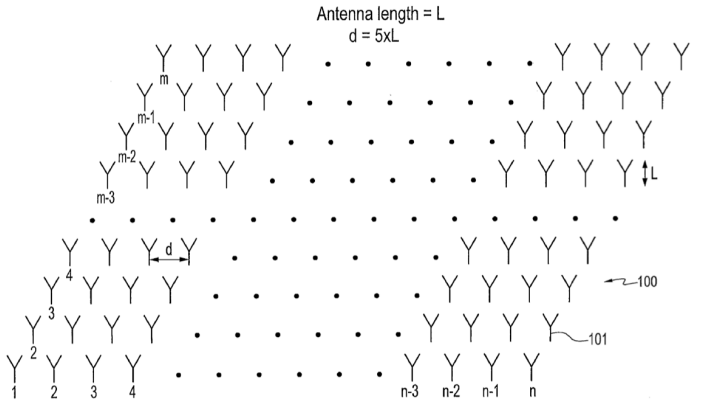
- 150 kHz – 8 GHz Bandwidth
- Down to 60 µm resolution
- Large device size



ERX+ device in use [4]



Half loop antenna layouts [4]

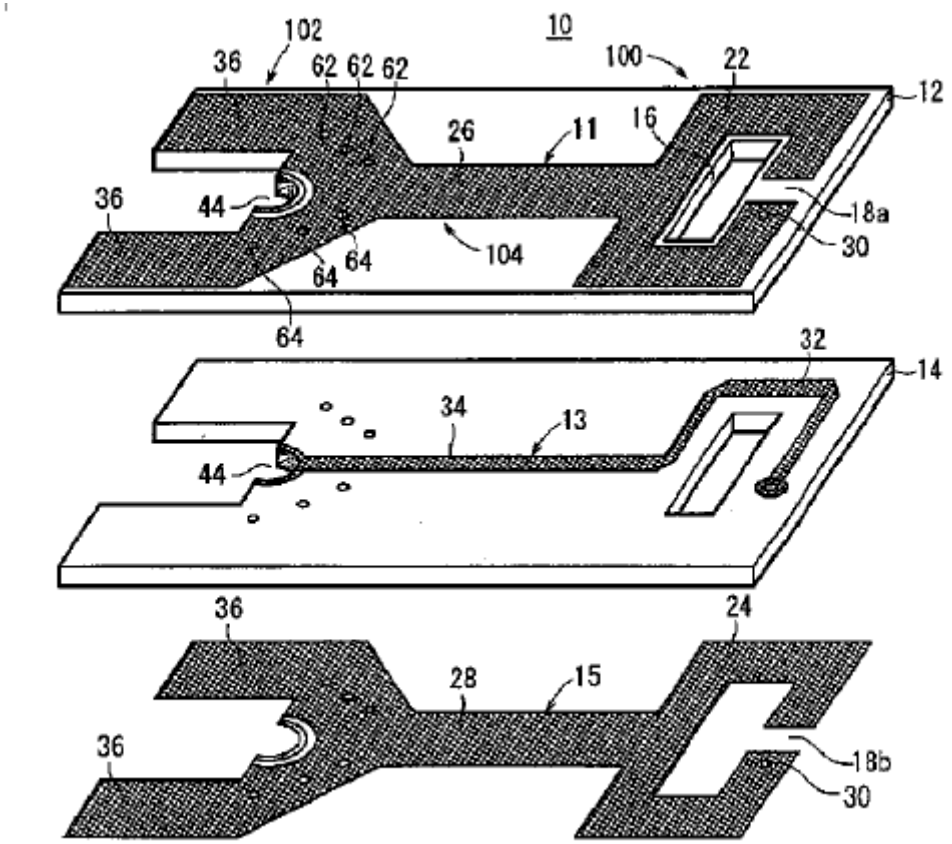


[4] Nyshadham, A., Patton, R., & Jin, J. (2010, March 2). Multichannel Absorberless Near Field Measurement System. Patent No. 8,502,546

Existing methodologies

Tohoku University Shielded Loop

- Wide bandwidth
  - 1 – 5 GHz
- Highest resolution
  - 300 μm
- Small probe
  - 600 μm x 600 μm
- Shielded loop design has been replicated by others



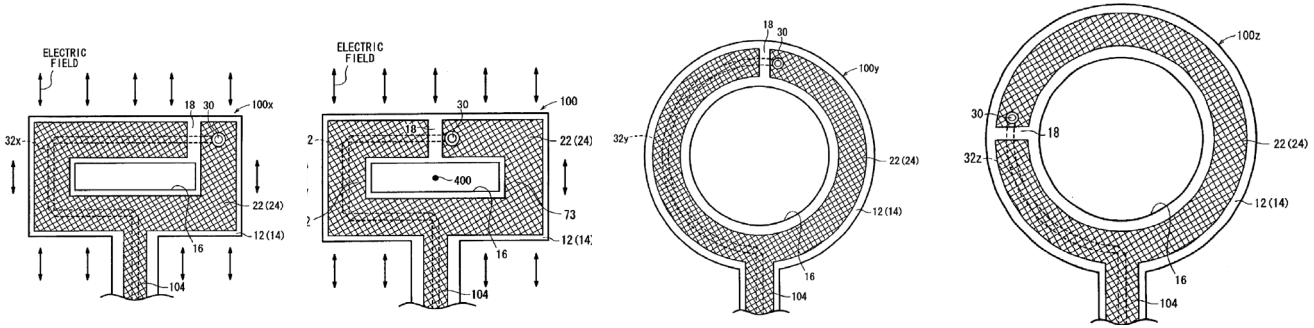
2005 Patented Loop [5]

[5] Miyazawa, Y., Kaminishi, K., Yamaguchi, M., & Arai, K. (2005, February 15). Magnetic Sensor, Side-Opened TEM Cell, and Apparatus Using Such Magnetic Sensor and Side-Opened TEM Cell. Patent No. 6,856,131

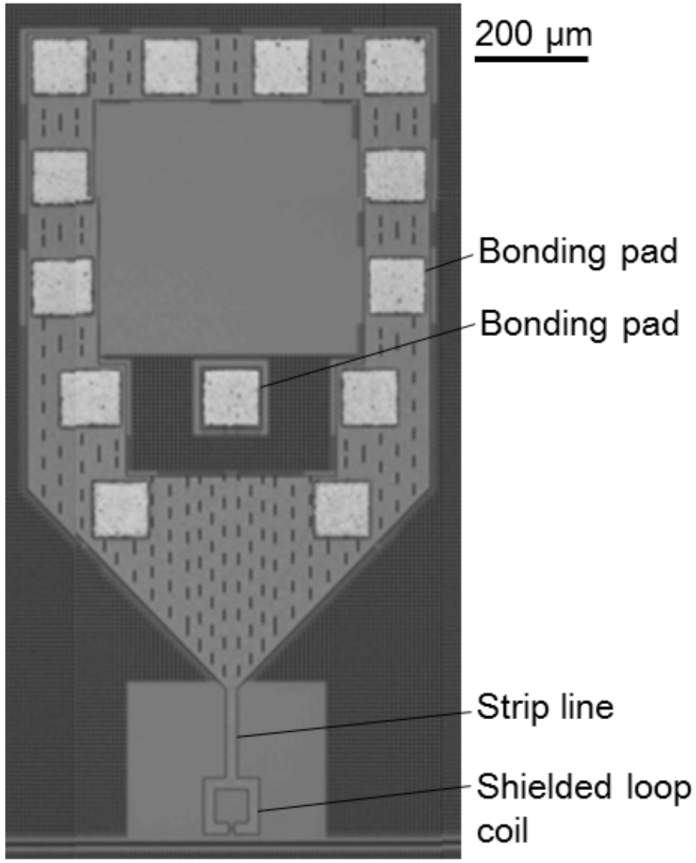
Existing methodologies

Tohoku University Shielded Loop

- Smaller size but higher resolution
  - Down to 60 μm x 60 μm
  - Resolution down to 10s of micrometers
- Low sensitivity
  - All designs require large amplification due to small size
  - LNA limited to 3 GHz



Tohoku Loop Variations [5]



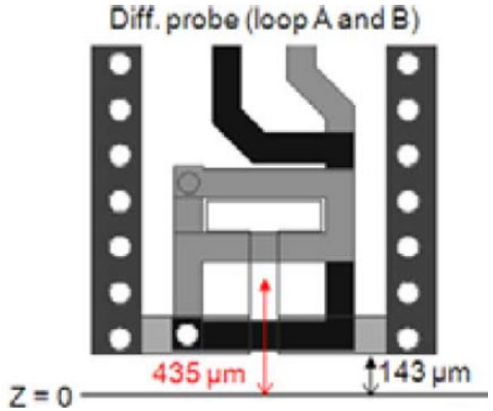
Smallest Tohoku Probe Overview [6]

[6] M. Yamaguchi, S. Muroga, S. Nanba, K. Arai, K. Yanagi and Y. Endo, "A 60×60μm2 size planar shielded loop probe for low lift-off on-chip magnetic near field measurements," 2013 *International Symposium on Electromagnetic Compatibility*, 2013, pp. 977-980.

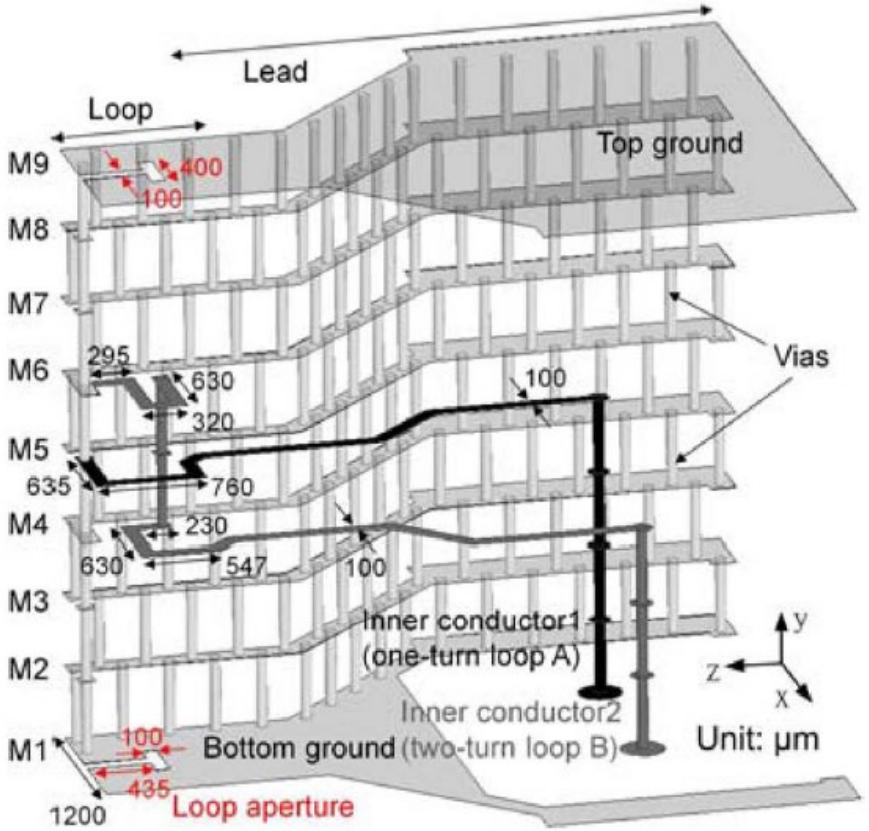
Existing methodologies

Chou Differential Probe

- In differential mode, performs with higher sensitivity than single loops of the same size
- Can be minimized for higher resolution
- Possible bandwidth sacrifice due to difference in electrical length of the two loops
- Higher resolution when the two outputs are in balance



Inner loops for differential probe [7]



Chou expanded probe diagram [7]

[7] Y. Chou and H. Lu, "Space difference magnetic near-field probe with spatial resolution improvement," in IEEE *Transactions on Microwave Theory and Techniques*, vol. 61, no. 12, pp. 4233-4244, Dec. 2013, doi: 10.1109/TMTT.2013.2288089.

Operational tradeoffs

Resolution vs. Sensitivity

- High resolution typically needs a small probe
- Smaller probes have lower sensitivity and require the addition of an amplifier
- Amplifiers can limit the bandwidth of the probe

Bandwidth vs. Size

- The bandwidth of the probe is limited by the size
- Lower frequency detection is necessary, so we are looking for a broadband approach
- Larger size −> lower resolution

Preliminary investigation of shielded resonant loops

Primary desired characteristics are in direct conflict

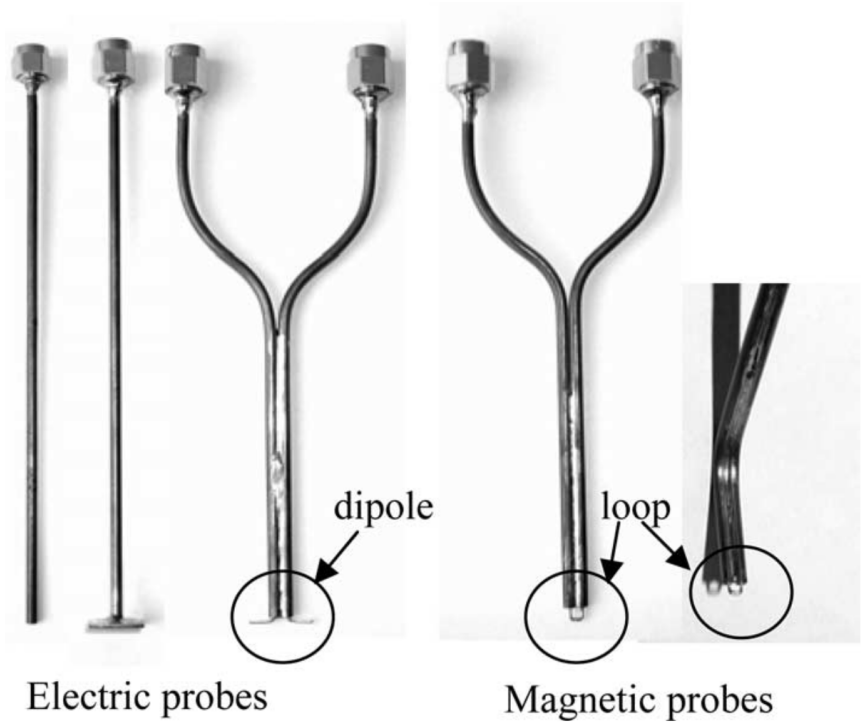
- Resolution and size vs. bandwidth and sensitivity
- What is the bar for sensitivity?
- What are methods to increase resolution without decreasing the size of the probe?
- What are methods to increase bandwidth while decreasing size?

Next Steps:

- Fully leverage prior work
- Focus on an array approach to achieve high resolution without sacrificing sensitivity

Preliminary investigation of shielded resonant loops

- Shielded loop offered best sensitivity results
  - Suppresses common mode currents due to electric field [8]
  - This is important for sensitivity, as this would protect the signal from noise
- Goal to understand the shielded loop and its operation over all frequency regimes
  - Potential for broadband application
  - Can be miniaturized for high resolution
- Combined with Baudry coaxial experimentation
  - Good resolution when used with positioner



Coaxial probes used for EMI field map [9]

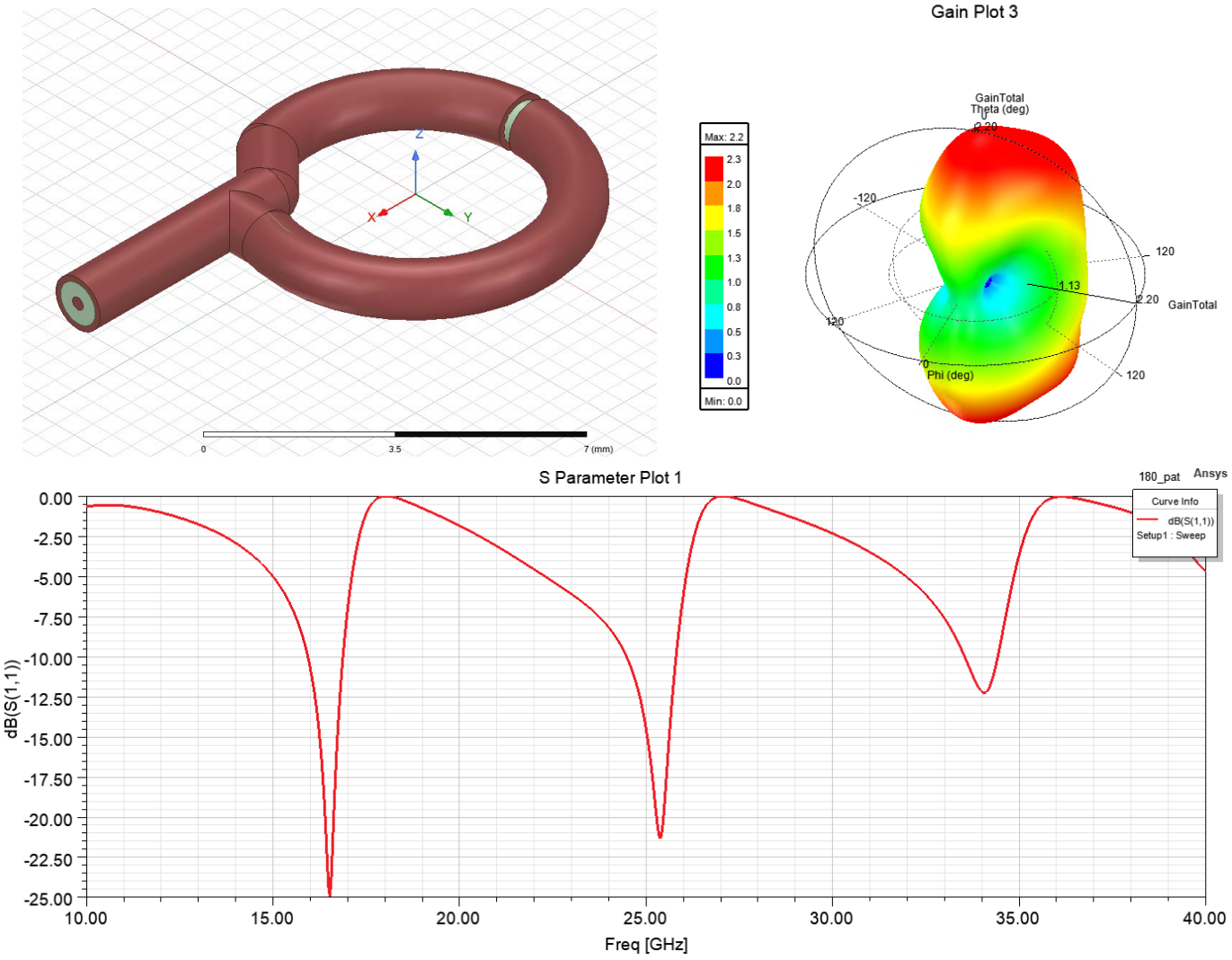
[8] Sivaraman, Nimisha. (2017). Design of magnetic probes for near field measurements and the development of algorithms for the prediction of EMC. *Compatibility*, 2013, pp. 977-980.

[9] D. Baudry, C. Arcambal, A. Louis, B. Mazari and P. Eudeline, "Applications of the near-field techniques in EMC investigations," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 49, no. 3, pp. 485-493, Aug. 2007, doi:10.1109/TEMC.2007.902194.

Preliminary investigation of shielded resonant loops

Creation of coaxial loop

- Exploration of different shield gaps
  - Varied in width and location
- Many possibilities given high number of degrees of freedom
  - Loop size
  - Gap width
  - Gap location
- Potentially offers higher sensitivity and larger bandwidth
- High resolution from array of loops



Sample coaxial loop and frequency response

Conclusions and Future Work

Conclusions

- Limitations on current designs require a different approach for our goals
- Array of coaxial loops
  - Possible solution to conflict between resolution and sensitivity, as arraying these loops could result in higher resolution without sacrificing sensitivity
  - Would avoid the need for a large amplifier

Future Work

- Explore near field behavior of loop
- Investigate methods to array and tune these loops

References

[1] Pepitone, J. (2022, April 21). *5 ways the chip shortage is rewiring tech*. IEEE Spectrum. Retrieved June 29, 2022, from https://spectrum.ieee.org/chip-shortage-rewiring-tech

[2] *CircuitScan 1000*. Micro Magnetics Sensible Solutions. (n.d.). Retrieved June 24, 2022, from https://www.micromagnetics.com/products_circuit_scan.html

[3] *Electric field measurement system: EMAG Technologies Inc..* EMAG Technologies Inc. | Innovative RF Solutions. (2019, May 8). Retrieved June 24, 2022, from https://emagtech.com/neoscan-system/

[4] Nyshadham, A., Patton, R., & Jin, J. (2010, March 2). Multichannel Absorberless Near Field Measurement System. Patent No. 8,502,546

[5] Miyazawa, Y., Kaminishi, K., Yamaguchi, M., & Arai, K. (2005, February 15). Magnetic Sensor, Side-Opened TEM Cell, and Apparatus Using Such Magnetic Sensor and Side-Opened TEM Cell. Patent No. 6,856,131

[6] M. Yamaguchi, S. Muroga, S. Nanba, K. Arai, K. Yanagi and Y. Endo, "A 60×60μm2 size planar shielded loop probe for low lift-off on-chip magnetic near field measurements," 2013 *International Symposium on Electromagnetic Compatibility*, 2013, pp. 977-980.

[7] Y. Chou and H. Lu, "Space difference magnetic near-field probe with spatial resolution improvement," in IEEE *Transactions on Microwave Theory and Techniques*, vol. 61, no. 12, pp. 4233-4244, Dec. 2013, doi: 10.1109/TMTT.2013.2288089.

[8] Sivaraman, Nimisha. (2017). Design of magnetic probes for near field measurements and the development of algorithms for the prediction of EMC. *Compatibility*, 2013, pp. 977-980.

[9] D. Baudry, C. Arcambal, A. Louis, B. Mazari and P. Eudeline, "Applications of the near-field techniques in EMC investigations," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 49, no. 3, pp. 485-493, Aug. 2007, doi: 10.1109/TEMC.2007.902194.