Standoff Through-the-Wall Sensing at Ka-Band Microwave

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ABSTRACT

Conventional microwave remote sensing/imaging of through-the-wall objects made of different materials is usually performed at frequencies below 3 GHz that provide relatively low spatial resolution. In this paper, we evaluate the ability and sensitivity of high-frequency microwave or millimeter wave standoff sensing of through-the-wall objects to achieve high spatial resolution. The target under study is a sandwich structure consisting of different object materials placed between two wall blocks. An Agilent® PNA-X series (model N5245A) vector network analyzer is used to sweep over the entire Ka-band (26.5 GHz to 40 GHz). The beam is then directed to a standard rectangular horn antenna and collimated by a 6-inch-diameter Gaussian lens towards the sandwich structure (wall block/object/wall block). The reflected electromagnetic wave is picked up by the same system as the complex S-parameter S₁₁. Both amplitude and phase of the reflected signal are used to recognize different materials sandwiched between the cement blocks. The experimental results are compared with the theoretical calculations, which show satisfactory agreement for the cases evaluated in this work.

Keywords: Standoff sensing, imaging, microwave, millimeter wave, S-parameter, Gaussian lens

INTRODUCTION

Compared to high-frequency electromagnetic waves such as millimeter wave (30-300 GHz [1-37]) and optics [38-48], the long-range and penetrative nature of microwave [49-61] through optically opaque dielectric materials makes it an ideal candidate for Through-the-Wall Imaging (TWI) of distant or inaccessible objects with the required spatial resolution. For such reason, recently, microwave standoff/remote TWI or sensing has attracted considerable amount of interest [62-69].

Potential Applications

The penetration property of the electromagnetic wave has found various industrial, civil and military applications [67, 70-75]. Various techniques at different frequency ranges have been extensively explored in the past decades. Most investigations were performed at the lower frequency range of microwaves, i.e., from DC to 3 GHz. This is because microwave attenuates less in this frequency range and in turn provides larger penetration depth [68]. What’s more, there are commonly three operation modes: CW, FMCW and pulse. Table 1 provides some typical applications of TWI that are separated into 3 categories:

- Human inside Building
Through the wall searching and identification of human subjects is of great interest for many purposes, which include searching for 1) trapped human subjects after disasters such as fires, flooding, tornado etc.; 2) terrorists or hostages inside enclosed structures during counter-terrorism or rescue operations; and 3) soldiers in the battlefield. For example through-the-wall vital signs detection and monitoring using UWB (Ultra-Wide Band) radar signal has been investigated by [70] and X-band CW (Continuous Wave) radar has been studied in [67].

- **Buried Humans**

Searching for buried human is an important application of TWI. Typical examples are: 1) buried humans under rubble after earthquakes; 2) buried humans under the snow after an avalanche; and 3) humans hidden or lost inside forest. For example, in [71], UHF-band and L-band CW radars are used to detect human subjects buried under simulated earthquake rubble; also S-band radar is used to detect buried human subjects during snow avalanche in [72].

- **Hidden Object Inspection**

The penetration property of the electromagnetic wave can be used for noncontact inspection applications such as 1) hidden objects inside walls, 2) buried landmine, cables, and pipes etc., and 3) underground structures such as soil, rock stratigraphy, ice depth, and hidden tunnels for illegal immigration and transport of illicit materials. For example, [73] used an L-band FMCW (Frequency Modulated Continuous Wave) radar for detection of hidden objects inside walls, [74] investigated an S-band/C-band/Ku-band CW radar for detection of under-surface hidden objects, and [75] used a VHF airborne pulse radar for remote sensing of underground buried objects.

Table 1 Some Typical Applications of TWI

| Research Category                      | Year | Operation Modes | Frequency Band                      | Experiment or Theory |
|----------------------------------------|------|-----------------|-------------------------------------|----------------------|
| Humans inside Building                 | [70] | Pulse           | X-band: 10 GHz                      | Experiment           |
|                                        | [67] | CW              | X-band: 10 GHz                      |                      |
| Buried Humans                          | [71] | CW              | UHF-band/L-band: 450 MHz/1150 MHz   | Experiment           |
|                                        | [72] |                 | S-band: 2.42 GHz                    |                      |
| Hidden Object Inspection               | [73] | FMCW            | L-band: 1-2 GHz                     | Experiment           |
|                                        | [74] | CW              | S-band/C-band/Ku-band: 3.6-4.0 GHz/5.8-6.8 GHz/14-15 GHz | Experiment |
|                                        | [75] | Pulse           | VHF: 50 MHz/100 MHz                 | Simulation & Experiment |

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**Contribution of This Paper**
One disadvantage of low frequency microwaves is its relatively low spatial resolution limited by the diffraction effect of electromagnetic waves. Higher frequency microwave techniques have also been investigated by other researchers primarily for nondestructive evaluation (NDE) of layered materials ([76-80]). Those studies on the other hand have been limited mostly to measurements over a relatively narrow band. In this paper, we investigate TWI at the upper end of microwave and the lower end of millimeter wave (mmW) spectrum covered by the Ka-band (26.5 GHz to 40 GHz), aimed at achieving higher spatial resolution. Experimental sensing of various materials sandwiched between two cement blocks in the Ka band is compared with the theoretical calculations to validate the feasibility of standoff through-the-wall sensing/imaging ability at such a high frequency range.

**EXPERIMENTAL SETUP**

The experimental setup used to investigate the concept of mmW TWI is shown in Fig. 1. The microwave apparatus consists of a 4-port Agilent® PNA-X series (model N5245A) vector network analyzer (VNA) for stepping through frequencies from 26.5 GHz to 40 GHz, a Ka-band standard rectangular horn antenna, and a 6-inch-diameter Gaussian horn antenna for collimating the beam. The plane wave propagates towards a sandwiched structure which is perpendicular to the beam path and is located ~30 inches away from the lens. The reflected wave is picked up by the same Ka-band horn antenna and is processed by the VNA to determine the complex S_{11} parameter (reflection coefficient). The sandwich structure is composed of two wall blocks (1.4-inch thick cement) with a 7-inch spacing where different materials can be placed. A LabVIEW® program running on a computer was developed for recording of the S_{11} parameter and for further processing.

![Fig. 1 Experimental setup of the standoff through-the-wall sensing of different objects: water, soil, rocks, and metal plate etc. The object is sandwiched between two wall blocks to form the sandwich structure. R is the range of the measurement.](image)

**THEORETICAL SIMULATION**

Figure 2 depicts the simplified numerical model of the experimental setup shown in Fig. 1. Without loss of generality, in the far field region the collimated beam can be approximated by an incident plane wave which reduces the model to plane wave incidence upon a layered dielectric structure. The problem may then be readily solved through the boundary matching method on all four boundaries separated by different materials. In reference to Fig. 2, from left to right, boundary #1 is air/wall-block boundary, boundary #2 is wall-block/object boundary, boundary #3 is object/wall-
block boundary, and boundary #4 is wall-block/air boundary. In reference to Table 1, the electric field (E-field) and magnetic field (H-field) inside each of the three layers of the target structure can be expressed as forward and backward propagating waves [81],

![Simplified model of plane wave propagation through the wall-block/object/wall-block sandwich structure.](image)

**Fig. 2 Simplified model of plane wave propagation through the wall-block/object/wall-block sandwich structure.**

| Regions | #1: Air | #2: Wall Block | #3: Object | #4: Wall Block | #5: Air |
|---------|---------|----------------|------------|----------------|---------|
| E-field | $e^{-jkz}$ | $ae^{-j\gamma_w z} + be^{-j\gamma_e z}$ | $ae^{-j\gamma_o z} + be^{-j\gamma_e z}$ | $ae^{-j\gamma_w z} + be^{-j\gamma_e z}$ | $ae^{-j\gamma_o z} + be^{-j\gamma_e z}$ |
| H-field × jμ | $jk(e^{-jkz} - re^{jkz})$ | $\gamma_w(\alpha e^{-j\gamma_w z} - \beta e^{-j\gamma_e z})$ | $\gamma_o(\alpha e^{-j\gamma_o z} - \beta e^{-j\gamma_e z})$ | $\gamma_w(\alpha e^{-j\gamma_w z} - \beta e^{-j\gamma_e z})$ | $\gamma_o(\alpha e^{-j\gamma_o z} - \beta e^{-j\gamma_e z})$ |

where $\gamma_w$ and $\gamma_o$ are wave propagation constants that include the attenuation effect inside the wall block and inside the object, respectively. As shown in Table 2, the boundary conditions at each interface may then be obtained by enforcing the continuity of both E-field and H-field obtained,

**Table 2. E/H-field Boundary Conditions on Each Boundary**

| Boundaries | #1: Air/Wall Block | #2: Wall Block/Object | #3: Object/Wall Block | #4: Wall Block/Air |
|------------|-------------------|-----------------------|----------------------|-------------------|
| E-field Boundary Condition | $1 + r = \alpha + \beta$ | $ae^{-j\gamma_w z} + be^{-j\gamma_e z}$ | $ae^{-j\gamma_o z} + be^{-j\gamma_e z}$ | $ae^{-j\gamma_w z} + be^{-j\gamma_e z}$ |
| H-field Boundary Condition | $jk(1-r) = \gamma_w(\alpha - \beta)$ | $\gamma_w(\alpha e^{-j\gamma_w z} - \beta e^{-j\gamma_e z})$ | $\gamma_o(\alpha e^{-j\gamma_o z} - \beta e^{-j\gamma_e z})$ | $\gamma_w(\alpha e^{-j\gamma_o z} - \beta e^{-j\gamma_e z})$ |

where $k$ is the wave vector in the air, $t_w$ and $t_o$ are the thickness of the wall block and the object, respectively; $\gamma_w$ and $\gamma_o$ are the propagation constant of the wall block and the object, respectively.

![Table 2. E/H-field Boundary Conditions on Each Boundary](image)
The boundary conditions in Table 2 can be readily solved in MATLAB® for all eight unknowns (i.e., $r, \alpha, \beta, \theta, \rho, \chi, \xi,$ and $\tau$) since we have eight boundary conditions. In matrix form, Table 2 reduces to,

$$M(f, e_a, e_o, t_w, t_o) \times \bar{u}(\alpha, \beta, \theta, \rho, \chi, \xi) = [1; jk; 0; 0; 0; 0; 0]^T,$$

where $f$ is the frequency, and $e_a, e_o$ are the dielectric constant of the wall block and the object, respectively. The calculated results and their comparison with the experimental results will be discussed in the following sections.

**EXPERIMENTAL RESULT**

In our experiment, 1601 frequencies evenly distributed between 26.5 GHz and 40 GHz were recorded for all the measurement scenarios. The IF-bandwidth of the VNA was set at 10 Hz to increase the Signal to Noise Ratio (SNR), which is inversely proportional to the IF-bandwidth.

**System calibration**

Due to the existence of background stray field $E_b$, we needed to calibrate our measurement system. The measured S-parameter $S_{11}$ can be expressed as follows [57],

$$S_{11} = (E_b + E_r)F(f) = E_r(e_b + r)F(f),$$

where $E_b, E_r,$ and $E_r$ are the background stray field, the reflected field due to the structure and the incident field, respectively, and $F(f)$ is the transfer function of the system. The goal is to ultimately extract the true reflection signal $r$ from the measurements. The S-parameter for the background $S_{11}^b$ and the S-parameter for the reflection from a metal surface $S_{11}^m$, which are measurable quantities that can be expressed as follows,

$$S_{11}^b = E_r e_b F(f),$$

$$S_{11}^m = E_r (e_b - r)F(f),$$

from which one gets,
By combining Eq. (2) and Eq. (5), the true reflection coefficient from the structure is then given by,

$$r = \frac{S_{11} - S_{11}^b}{S_{11}^b - S_{11}^m}.$$  \hspace{1cm} (6)

**Dielectric constant of wall block**

In order to solve Eq. (1), the dielectric constant of the wall block has to be first determined. This was obtained through direct measurement of the S-parameter $S_{11}$ at 101 frequency points within the Ka band for an individual wall block. The measurement data may then be fitted by using the following theoretical formula [57],

$$r_w = \frac{\left[ \frac{1}{\varepsilon_w} - 1 \right] \left[ 1 - \exp(-j2k_w t_w) \right]}{\left[ \frac{1}{\sqrt{\varepsilon_w}} + 1 \right]^2 - \left[ \frac{1}{\sqrt{\varepsilon_w}} - 1 \right]^2 \exp(-j2k_w t_w)}.$$  \hspace{1cm} (7)

By using this approach, we obtained an average value of $\varepsilon_w = 12.4(1 - j0.003)$ for the dielectric constant of the wall block. Comparison of the experimental result with that calculated using Eq. (7) is shown in Fig. 3.

**$S_{11}$ of the sandwich structure**

The S-parameter $S_{11}$ for sandwiched water object is shown in Fig. 4, together with the theoretical results calculated according to Eq. (1). A snapshot of data in Fig. 3 over a narrow frequency range is shown in Fig. 5. The parameters used for fitting are $\varepsilon_w = 12.4(1 - j0.003)$, obtained from Fig. 3, and water, as the sandwiched object, with a dielectric constant $\varepsilon_o = 77$. The sandwich structure was approximately 30 inches ($R \sim 30''$) away from the antenna.
Fig. 3 Experimental reflection is fitted to theoretical calculation, i.e., Eq. (7), to obtain the dielectric constant of the wall block used in the experiment, which was determined to be $\varepsilon_w = 12.4(1 - j0.003)$.

Fig. 4 Experimental and calculated S-parameter $S11$ for wall block/water/wall block sandwich structure where $\varepsilon_w = 12.4(1 - j0.003)$ and $\varepsilon_{water} = 77$ for water.
Following the validation of the procedure for extraction of dielectric properties of test object, several experiments were carried out by using different materials sandwiched between the two wall blocks, i.e., soil, rocks and metal. To demonstrate the ability to see the contrast between different objects behind the wall, the difference (with that of water as the object) of the S-parameter, \( \Delta S_{11} = S_{11} - S_{11}(\text{water}) \), for three different materials is shown in Fig. 6. Both the amplitude and the phase spectrum are displayed. Once again, Fig. 7 provides a snapshot of Fig. 6, allowing for more
detailed observation of the data over a narrow bandwidth. From the S-parameter contrast, one can clearly distinguish different materials by combining both the amplitude and the phase information.

**DISCUSSION**

We have demonstrated the feasibility of standoff through-the-wall sensing of different materials at Ka band using a wide-band stepped-frequency measurement approach. Both theoretical and experimental results show promise for application of this technique to TWI at these relatively high microwave frequencies for high resolution imaging of hidden objects (e.g., covered by wall, soil, snow, etc.). The detection range can be estimated by Friis transmission equation,

\[
P_d(\text{min.}) = P_t G^2 \left( \frac{\lambda}{4\pi R} \right)^2 \Rightarrow R = \frac{\lambda}{4\pi} \sqrt{\frac{P_t}{P_d(\text{min.})}},
\]

where \( R \) is the range; \( P_t \) and \( P_d(\text{min.}) \) are the transmitted and the minimum detectable power by the system, respectively, \( \lambda \) is the operating wavelength and \( G \) is the gain of the system.

Future extension of this monostatic setup to mobile systems with multiple antennas (array configuration) is expected to provide even higher resolution for 2D TWI applications. If combined with a frequency sweeping function, 3D TWI is also possible, allowing identification of objects behind a wall with known dielectric constant and thickness [Ahmad, 2008].

**CONCLUSION**

Through-the-wall sensing of various materials at Ka band have been investigated using a monostatic stepped-frequency experimental setup. A network analyzer was used to measure S-parameter \( S_{11} \) of an object within a layered structure over the frequency range of 26.5 GHz to 40 GHz. The target in this work was a wall-block/object/wall-block sandwich structure. The hidden objects in the middle layer included water, soil, rocks, and metal. Combination of the amplitude and the phase information of the reflected signal shows clear contrast among various objects sandwiched between two wall
blocks. Theoretical calculations based on a plane wave solution obtained using a boundary matching technique were also performed. Numerical results showed good agreement with that of the experimental data. The results of this investigation suggest that high-resolution mmW through-the-wall sensing and imaging techniques could provide a viable alternative to low-frequency microwave TWI.

REFERENCES

1. S. Liao, Multi-frequency beam-shaping mirror system design for high-power gyrotrons: Theory, algorithms and methods, ProQuest Dissertations And Theses; Thesis (Ph.D.)--The University of Wisconsin - Madison, 2008.; Publication Number: AAI3314260; ISBN: 9780549633167; Source: Dissertation Abstracts International, Volume: 69-05, Section: B, pp. 1-245. https://ui.adsabs.harvard.edu/abs/2008PhDT.......81L/abstract or https://dl.acm.org/doi/book/10.5555/1467404

2. L. Ou, S. Liao, Z. Qin, and H. Yin, “Millimeter Wave Wireless Hadamard Image Transmission for MIMO enabled 5G and Beyond,” IEEE Wireless Communications, pp. 1536-1284, 2020. DOI: 10.1109/MWC.001.2000081

3. S. Liao, Z. Wang, L. Ou, and Y. Peng, “A Harmonics Interferometric Doppler Sensor With a Neon Lamp Detector,” IEEE Sensors Journal, pp. 1-1, 2020, DOI: 10.1109/JSEN.2020.2970055.

4. S. Liao, N. Gopalsami, S. Bakhtiari, T. W. Elmer, E. R. Koehl, and A. C. Raptis, “A novel interferometric sub-THz Doppler radar with a continuously oscillating reference arm,” IEEE Transactions on Terahertz Science and Technology, vol. 4, no. 3, pp. 307-313, Mar. 2014. DOI: 10.1109/TTHZ.2014.2307165

5. S. Liao et al., “Passive millimeter-wave dual-polarization imagers,” IEEE Transactions on Instrumentation and Measurement, vol. 61, no. 7, pp. 2042 - 2050, Feb. 2012. DOI: 10.1109/TIM.2012.2183032

6. N. Gopalsami, S. Liao, T. Elmer, E. Koehl, A. Heifetz, A. Raptis, L. Spinoulas, and A. Katsaggelos, “Passive millimeter-wave imaging with compressive sensing,” Optical Engineering, vol. 51, no. 9, pp. 091614-1-9, Sep. 2012. DOI: 10.1117/1.OE.51.9.091614

7. S. Bakhtiari, T. Elmer, M. Cox, N. Gopalsami, A. Raptis, S. Liao, I. Mikhelson and A. Sahakian, “Compact Millimeter-Wave Sensor for Remote Monitoring of Vital Signs,” IEEE Transactions on Instrumentation and Measurement, vol. 61, no. 3, pp. 830-841, Mar. 2012, DOI: 10.1109/TIM.2011.2171589.

8. S. Liao, N. Gopalsami, A. Venugopal, A. Heifetz, and A. C. Raptis, “An efficient iterative algorithm for computation of scattering from dielectric objects,” Optics Express, vol. 19, no. 3, pp. 3304-3315, 2011. DOI: 10.1364/OE.19.003304

9. S. Bakhtiari, S. Liao, T. Elmer, N. Gopalsami, and A. C. Raptis, “A real-time heart rate analysis for a remote millimeter wave I-Q sensor,” IEEE Transactions on Biomedical Engineering, vol. 58, no. 6, pp. 1839-45, Mar. 2011. DOI: 10.1109/TBME.2011.2122335

10. A. Heifetz, H. T. Chien, S. Liao, N. Gopalsami, and A. C. Raptis, “Millimeter-wave scattering from neutral and charged water droplets,” Journal of Quantitative Spectroscopy and Radiative Transfer, vol. 111, no. 17-18, pp. 2550-2557, 2010. DOI: 10.1016/j.jqsrt.2010.08.001

11. S. Liao and R. J. Vernon, “A fast algorithm for computation of electromagnetic wave propagation in half-space,” IEEE Trans. on Antennas and Propagation, vol. 57, no. 7, pp. 2068-2075, Jul. 2009. DOI: 10.1109/TAP.2009.2021890
12. S. Liao, “Miter bend mirror design for corrugated waveguides,” *Letters of Progress in Electromagnetics Research*, vol. 10, pp. 157-162, 2009. DOI: 10.2528/PIER09062103

13. S. Liao and R. J. Vernon, “Sub-THz beam-shaping mirror designs for quasi-optical mode converter in high-power gyrotrons,” *Journal of Electromagnetic Waves and Applications*, vol. 21, no. 4, pp. 425-439, 2007. DOI: 10.1163/15693930779367332

14. S. Liao and R. J. Vernon, “A fast algorithm for wave propagation from a plane or a cylindrical surface,” *International Journal of Infrared and Millimeter Wave*, vol. 28, no. 6, pp. 479-490, 2007. DOI: 10.1007/s10762-007-9213-0

15. S. Liao, “The Taylor Interpolation through FFT Algorithm for Electromagnetic Wave Propagation and Scattering,” arXiv:physics/0610057, Oct. 2006. [https://arxiv.org/abs/physics/0610057](https://arxiv.org/abs/physics/0610057)

16. S. Liao and L. Ou, “High-speed Millimeter-wave 5G/6G Image Transmission via Artificial Intelligence,” 2020 Asia-Pacific Microwave Conference (APMC 2020), Hong Kong SAR, PR China, 8-11 December, 2020. arXiv:2007.03153: [https://arxiv.org/abs/2007.03153](https://arxiv.org/abs/2007.03153)

17. I. V. Mikhelson, S. Bakhtiari, T. W. E. II, S. Liao, and A. V. Sahakian, “Remote sensing of heart rate using millimeter-wave interferometry and probabilistic interpolation,” in *Proceedings SPIE 8719, Smart Biomedical and Physiological Sensor Technology X*, 2013, vol. 87190M. DOI: 10.1117/12.2015282

18. S. Liao, N. Gopalsami, S. Bakhtiari, T. Elmer, and A. C. Raptis, “A novel interferometric millimeter wave Doppler radar,” *2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Minneapolis, MN, 2013, pp. 387-391. DOI: 10.1109/I2MTC.2013.6555445

19. S. Liao et al., “Millimeter Wave Doppler Sensor for Nondestructive Evaluation of Materials,” *21st Annual Research Symposium & Spring Conference 2012*, Dallas, TX USA, 2012. arXiv:2007.00195: [https://arxiv.org/abs/2007.00195](https://arxiv.org/abs/2007.00195)

20. S. Liao, S. Bakhtiari, T. Elmer, A. C. Raptis, I. V. Mikhelson, and A. V. Sahakian, “Millimeter wave I-Q standoff biosensor,” in *Proceedings SPIE 8371, Sensing Technologies for Global Health, Military Medicine, Disaster Response, and Environmental Monitoring II; and Biometric Technology for Human Identification IX*, 2012, vol. 83711D. DOI: 10.1117/12.924241

21. N. Gopalsami, S. Liao, T. Elmer, E. R. Koehl, and A. C. Raptis, “Evaluation of passive millimeter wave system performance in adverse weather,” in *Proceedings SPIE 8362, Passive and Active Millimeter Wave Imaging XV*, 2012, vol. 83620I. DOI: 10.1117/12.919212

22. N. Gopalsami, T. W. Elmer, S. Liao, R. Ahern, A. Heifetz, A. C. Raptis, M. Luessi, D. Babacan and A. K. Katsaggelos, “Compressive sampling in passive millimeter wave imaging,” in *Proceedings of SPIE 8022, Passive Millimeter-Wave Imaging Technology XIV*, 2011, vol. 80220I. DOI: 10.1117/12.886998

23. N. Gopalsami, S. Liao, T. Elmer, A. Heifetz and A. C. Raptis, “Compressive sampling in active and passive millimeter-wave imaging,” *2011 International Conference on Infrared, Millimeter, and Terahertz Waves*, Houston, TX, 2011, pp. 1-2. DOI: 10.1109/IRMMW-THz.2011.6105205

24. E. Buscarino, S. Liao, M. Perkins, B. Rock, U. Farid and R. Vernon, “High-Power Microwave Transmission and Mode Conversion Program,” *Report to USA DOE Office*, 2005, DOI: 10.2172/1210042

25. S. Liao, “Validity of image theorem under spherical geometry,” Marrakesh, Morocco, 2011. arXiv:2007.02000: [https://arxiv.org/abs/2007.02000](https://arxiv.org/abs/2007.02000)
26. S. D. Babacan, M. Luessi, L. Spinoulas, A. K. Katsaggelos, N. Gopalsami, T. Elmer, R. Ahern, S. Liao and A. Raptis, “Compressive passive millimeter-wave imaging,” 2011 18th IEEE International Conference on Image Processing, Brussels, 2011, pp. 2705-2708. DOI: 10.1109/ICIP.2011.6116227

27. N. Gopalsami, S. Liao, E. R. Koehl, T. W. Elmer, A. Heifetz, H.-T. Chien and A. C. Raptis, “Passive millimeter wave imaging and spectroscopy system for terrestrial remote sensing,” in Proceedings of SPIE 7670, Passive Millimeter-Wave Imaging Technology XIII, 2010, vol. 767003. DOI: 10.1117/12.850123

28. S. Liao, Vernon RJ and Neilson J., “A four-frequency mode converter with small output angle variation for a step-tunable gyrotron,” Proceedings of the 15th Joint Workshop On Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Ec-15. 477-482. DOI: 10.1142/9789812814647_0068

29. R. J. Vernon, S. Liao and J. Neilson, “A high-efficiency four-frequency mode converter design with small output angle variation for a step-tunable gyrotron,” in 2008 33rd International Conference on Infrared, Millimeter and Terahertz Waves, Pasadena, CA, USA, 2008. DOI: 10.1109/ICIMW.2008.4665569

30. S. Liao, “On the validity of physical optics for narrow-band beam scattering and diffraction from the open cylindrical surface,” Progress in Electromagnetics Research Symposium (PIERS), vol. 3, no. 2, pp. 158-162, 2007. DOI: 10.2529/PIERS060906142312

31. S. Liao, “Fast computation of electromagnetic wave propagation and scattering for quasi-cylindrical geometry,” Progress in Electromagnetics Research Symposium (PIERS), vol. 3, no. 1, pp. 96-100, 2007. DOI: 10.2529/PIERS06090605903

32. S. Liao, “Beam-shaping PEC mirror phase corrector design,” Progress in Electromagnetics Research Symposium (PIERS), vol. 3, no. 4, pp. 392-396, 2007. DOI: 10.2529/PIERS061005101313

33. S. Liao and R. J. Vernon, “The near-field and far-field properties of the cylindrical modal expansions with application in the image theorem,” 2006 Joint 31st International Conference on Infrared Millimeter Waves and 14th International Conference on Terahertz Electronics, Shanghai, 2006, pp. 260-260. DOI: 10.1109/ICIMW.2006.368468

34. S. Liao and R. J. Vernon, “The cylindrical Taylor-interpolation FFT algorithm,” 2006 Joint 31st International Conference on Infrared Millimeter Waves and 14th International Conference on Terahertz Electronics, Shanghai, 2006, pp. 259-259. DOI: 10.1109/ICIMW.2006.368467

35. S. Liao and R. J. Vernon, “On the image approximation for electromagnetic wave propagation and PEC scattering in cylindrical harmonics,” Progress In Electromagnetics Research, Vol. 66, 65-88, 2006. DOI: 10.2528/PIER06083002

36. S. Liao and R. J. Vernon, “On fast computation of electromagnetic wave propagation through FFT,” 2006 7th International Symposium on Antennas, Propagation & EM Theory, Guilin, 2006, pp. 1-4. DOI: 10.1109/ISAPE.2006.353495

37. S. Liao and R. J. Vernon, “A new fast algorithm for field propagation between arbitrary smooth surfaces,” 2005 Joint 30th International Conference on Infrared and Millimeter Waves and 13th International Conference on Terahertz Electronics, Williamsburg, VA, USA, 2005, pp. 606-607 vol. DOI: 10.1109/ICIMW.2005.1572687

38. S. Liao and L. Ou, “Bound States in Continuum and Zero-Index Metamaterials: A Review,” arXiv:2007.01361, Jul. 2020. https://arxiv.org/abs/2007.01361
39. S. Liao, “Optimal Feedback-Interferometric Fiber Laser Sensors,” 2019 Photonics & Electromagnetics Research Symposium - Fall (PIERS - Fall), Xiamen, China, 2019, pp. 63-65. DOI: 10.1109/PIERS-Fall48861.2019.9021883
40. Y. Peng and S. Liao, “On-chip ZIM-BiC Laser,” in 2019 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO), 2019, pp. 1-4. DOI: 10.1109/NEMO.2019.8853827.
41. S. Liao, “Spectral-domain MOM for Planar Meta-materials of Arbitrary Aperture Wave-guide Array,” in 2019 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO), 2019, pp. 1-4. DOI: 10.1109/NEMO.2019.8853816.
42. Y. Zeng Z. Tang, S. Liao and Y. Peng, “On-chip Coupler Using Zero-index Metamaterials,” 2019 Photonics & Electromagnetics Research Symposium - Fall (PIERS - Fall), Xiamen, China, 2019, pp. 1458-1460. DOI: 10.1109/PIERS-Fall48861.2019.9021503
43. Y. Peng and S. Liao, “ZIM Laser: Zero-Index-Materials Laser,” IEEE Journal on Multiscale and Multiphysics Computational Techniques, vol. 4, pp. 133-142, 2019, DOI: 10.1109/JMMCT.2019.2905368.
44. S. Liao and L. Ou, “High-Q Interstitial Square Coupled Microring Resonators Arrays,” IEEE Journal of Quantum Electronics, 23 April 2020. DOI: 10.1109/JQE.2020.2989809
45. S. Liao, T. Wong, and L. Ou, “Optimal feedback-interferometric fiber laser microphones,” Optics Letters, Optical Society of America (OSA), vol. 45, no. 2, pp. 423-426, Jan. 2020, DOI: 10.1364/OL.384225.
46. S. Liao and T. Wong, “Optimal Design of Feedback-Interferometric Fiber Laser Sensors,” IEEE Sensors Journal, vol. 19, no. 24, pp. 12016-12023, Dec. 2019, DOI: 10.1109/JSEN.2019.2936222.
47. S. Liao, T. Wong, Z. Wang, R. Wang, E. Clutter, and H.-T. Chien, “Miniature fiber laser microphones with graphene diaphragms,” 2018 IEEE Research and Applications of Photonics In Defense Conference (RAPID), Miramar Beach, FL, 2018, pp. 1-4. DOI: 10.1109/RAPID.2018.8508963
48. E. Clutter B. Matos, Z. Wang, R. Divan, A. Macrander and S. Liao, X-ray Writing of Optical Fiber Gratings with a nm-Mask, The American Vacuum Society (AVS) Prairie Chapter, The University of Chicago, IL USA, 2018. arXiv:2007.00683, https://arxiv.org/abs/2007.00683
49. S. Liao and L. Ou, “A Ping-Pong Computational Electromagnetics (CEM) Algorithm for 2D Antennas/Metasurfaces,” 2020 Asia-Pacific Microwave Conference (APMC 2020), Hong Kong SAR, PR China, 8-11 December, 2020. Preprint available at arXiv.
50. S. Liao and L. Ou, “Iterative Physical Optics (IPO) for Fast and Accurate Simulation of Reflector Antennas,” 2020 Asia-Pacific Microwave Conference (APMC 2020), Hong Kong SAR, PR China, 8-11 December, 2020. arXiv:2007.01861: https://arxiv.org/abs/2007.01861
51. S. Liao and L. Ou, “Ultra-sensitive Parity-Time Symmetry based Graphene FET (PTS-GFET) Sensors,” 2020 Asia-Pacific Microwave Conference (APMC 2020), Hong Kong SAR, PR China, 8-11 December, 2020. arXiv:2007.04567: https://arxiv.org/abs/2007.04567
52. Sanchith Padmaraj K. Nirish Patil and S. Liao, “A Compact Dual-band WiFi Energy Harvester,” 2019 Photonics & Electromagnetics Research Symposium - Fall (PIERS - Fall), Xiamen, China, 2019, pp. 1209-1212. DOI: 10.1109/PIERS-Fall48861.2019.9021903
53. Y. He Y. Li Z. Zhou H. Li Y. Hou S. Liao and P. Chen, “Wideband Epsilon-Near-Zero Supercoupling Control through Substrate-Integrated Impedance Surface,” Advanced Theory and Simulations, vol. 2, no. 8, p. 1900059, 2019, DOI: 10.1002/ads.201900059.
54. M. Hajizadegan, M. Sakhdari, S. Liao, and P.-Y. Chen, “High-Sensitivity Wireless Displacement Sensing Enabled by PT-Symmetric Telemetry,” IEEE Transactions on Antennas and Propagation, vol. 67, no. 5, pp. 3445-3449, May 2019, DOI: 10.1109/TAP.2019.2905892.
55. L. Zhu, N. Alkhaldi, H. M. Kadry, S. Liao, and P.-Y. Chen, “A Compact Hybrid-Fed Microstrip Antenna for Harmonics-Based Radar and Sensor Systems,” IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 12, pp. 2444-2448, Dec. 2018, DOI: 10.1109/LAWP.2018.2877674.
56. S. Liao et al., “Nuclear radiation induced atmospheric air breakdown in a spark gap,” IEEE Transactions on Plasma Science, vol. 40, no. 4, pp. 990-994, Mar. 2012. DOI: 10.1109/TPS.2012.2187343
57. S. Liao et al., “Microwave Remote Sensing of Ionized Air,” IEEE Geoscience and Remote Sensing Letters, vol. 8, no. 4, pp. 617-620, Jul. 2011, DOI: 10.1109/LGRS.2010.2098016.
58. K. Wang, H. T. Chien, S. Liao, L. P. Yuan, S. H. Sheen, S. Bakhtiari and A. C. Raptis, “Ultrasonic and electromagnetic sensors for downhole reservoir characterization,” in Proceedings of Thirty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 31 - February 2, 2011 SGP-TR-191.
arXiv:2007.00191: https://arxiv.org/abs/2007.00191
59. H. Soekmadji, S. Liao, and R. J. Vernon, “Experiment and simulation on TE10 cut-off reflection phase in gentle rectangular downtapers,” Letters of Progress in Electromagnetics Research, vol. 12, pp. 79-85, 2009. DOI: 10.2528/PIERL09090707
60. H. Soekmadji, S. Liao, and R. J. Vernon, “Trapped mode phenomena in a weakly overmoded waveguiding structure of rectangular cross section,” Journal of Electromagnetic Waves and Applications, vol. 22, no. 1, pp. 143-157, 2008. DOI: 10.1163/156939308783122706
61. S. Liao and A. Z. Genack, “Polarization correlation in a quasi-1-D random system,” in Frontiers in Optics 2008/Laser Science XXIV/Plasmonics and Metamaterials/Optical Fabrication and Testing, Rochester, New York, USA, 2008. DOI:10.1364/FIO.2008.FWV3
62. Aamna, M., Ammar, S., Rameez, T., Shabeeb, S., Rao, N. I., and Safwat, I., “2D Beamforming for Through-the-Wall Microwave Imaging Applications,” 2010 International Conference on Information and Emerging Technologies (ICIET), 14-16 June 2010.
63. Aftanas, M., Zaikov, E., Drutarovsky, M., and Sachs, J., “Through Wall Imaging of the Objects Scanned by M-sequence UWB Radar System,” Proceedings of the 18th International Conference Radioelektronika, Prague, Czech Republic, Apr. 2008, pp. 33-36.
64. Aftanas, M., “Signal Processing Steps for Objects Imaging through the Wall with UWB Radar,” 9th Scientific Conference of Young Researchers (SCYR), 2009.
65. Dehmollaian, M., “Simulation of Through-Wall Microwave Imaging: Forward and Inverse Models,” IEEE International Conference on Geoscience and Remote Sensing Symposium (IGARSS), 2006.
66. Ahmad, F., Zhang Y., and Amin, M. G., “Three-dimensional Wideband Beamforming for Imaging through a Single Wall,” IEEE Geoscience and Remote Sensing Letters, Vol. 5, No. 2, April 2008.
67. D’Urso M., Leone G., and Soldovieri F., “A Simple Strategy for Life Signs Detection via an X-band Experimental Set-up,” Progress In Electromagnetics Research C, Vol. 9, 119-129, 2009.
68. Yemelyanov, K. M., Engheta, N., Hoorfar, A., and McVay, J. A., “Adaptive Polarization Contrast Techniques for Through-Wall Microwave Imaging Applications,” IEEE Transactions on Geoscience and Remote Sensing, Vol. 47, No. 5, May 2009, pp. 1362-1374.

69. Johnson, J. T., Demir, M. A., and Majurec, N., “Through-Wall Sensing with Multifrequency Microwave Radiometry: a Proof-of-Concept Demonstration,” IEEE Transactions on Geoscience and Remote Sensing, Vol. 47, No. 5, May 2009, pp. 1281-1288.

70. Lubecke, V. M., O. Boric-Lubecke, A. Host-Madsen, and A. E. Fathy, “Through-the-Wall Radar Life Detection and Monitoring,” Proc. of Microwave Symposium 2007, 769-772, 2007.

71. Chen, K. M., Y. Huang, J. Zhang, and A. Norman, “Microwave Life-Detection Systems for Searching Human Subjects under Earthquake Rubble and behind Barrier,” IEEE Trans. Biomed. Eng., Vol. 27, 105-114, 2000.

72. Pieraccini, M., G. Luzi, D. Dei, L. Pieri, and C. Atzeni, “Detection of breathing and heartbeat through snow using a microwave transceiver,” IEEE Geoscience and Remote Sensing Letters, Vol. 5, 1, 57-59, 2008.

73. Botros A. Z., Olver A. D., Cuthbert L. G., and Farmer G., “Microwave Detection of Hidden Objects in Walls,” Electronics Letters, Vol. 20, No. 9, 1984.

74. Zhuravlev A., Bugaev, A., Ivashov, S., Razevig, V., and Vasiliev, I., “Microwave Holography in Detection of Hidden Objects under the Surface and Beneath Clothes,” General Assembly and Scientific Symposium, 2011 XXXth URSI, pp. 1-4, 2011.

75. Sen M. K., Stoffa P. L., and Seifoullaev R. K., “Numerical and Field Investigations of GPR: Toward an Airborne GPR,” Subsurface Sensing Technologies and Applications, Vol. 4, No. 1, 2003.

76. Bakhtiari, S., N. Qaddouni, S. Ganchev and R. Zoughi, "Microwave Non-Contact Examination of Disbond and Thickness Variation in Stratified Composite Media," IEEE Trans. on Microwave Theory and Tech., vol. 42, no. 3, Mar 1994.

77. Bakhtiari, S., N. Gopalsami, and A. C. Raptis, "Characterization of Delamination and Disbonding in Stratified Dielectric Composites by Millimeter Wave Imaging," Invited paper, Special Microwave Issue of Materials Evaluation, vol. 53, no. 4, 1995.

78. Zoughi, R., Gary, S., and Nowak, P. S., “Microwave Nondestructive Estimation of Cement Paste Compressive Strength,” ACI Materials Journal, 92(1): 64-70, 1995.

79. Bois, K., Benally, A., and Zoughi, R., “Microwave Near-field Reflection Property Analysis of Concrete for Material Content Determination,” IEEE Transactions on Instrumentation and Measurement, 49(1): 49-55, 2000.

80. Mubarak, K., Bois, K. J., and Zoughi, R., “A Simple, Robust and On-Site Microwave Technique for Determining Water-to-Cement (w/c) Ratio of Fresh Portland Cement-Based Materials,” IEEE Transactions on Instrumentation and Measurement, 50(5): 1255-1263, 2001.

81. Jackson, J. D., Classical Electrodynamics, 3rd ed., 1998.