SILO-Radar: Self-Injection Locked Oscillator based Radar

K Nirish Patil[1], Rutuja Mhatre[2], Praveni Saripella[3], Ankita Desai[4], Yimou Wang[5], Sayali Patil[6]*,
Akhila Kommireddy[7]* Shaolin Liao[8]*
Department of Electrical and Computer Engineering, *Illinois Institute of Technology*, Chicago, IL, USA
[1]npatil10@hawk.iit.edu; [2]rmhatre2@hawk.iit.edu; [3]psaripella@hawk.iit.edu; [4]adesai31@hawk.iit.edu;
[5]ywang461@hawk.iit.edu; [6]spatil48@hawk.iit.edu;,[7]akommireddy@hawk.iit.edu;
[8]sliao5@iit.edu ORCID: 0000-0002-4432-3448

***Abstract*—A compact Self-Injection Locked Oscillator based Doppler Radar (SILO-Radar) at 5 GHz has been studied, analytically and numerically. The SILO-Radar consists of just a cross-coupled oscillator and a Schottky diode baseband detector, with the help of the Hilbert transform at the baseband to extract the Doppler phase information. Both analytical analysis and PSpice simulation have been performed to verify the validity of the SILO-Radar. The compact, low-power and low-cost SILO-Radar has many potential consumer applications such as auto-driving radars, Unmanned Aerial Vehicle (UAV) navigation radars, remote heartbeat/respiration healthcare biomedical radars and so on.**

***Index Terms*—Self-Injection Locked Oscillator (SILO), Doppler radar, auto-driving, cross-coupled oscillator.**

I. INTRODUCTION

Making use of the remote capability of the electromagnetic waves from the Radio-Frequency (RF) wave to the high-frequency optics wave [1]- [63], Doppler sensors such as RF/microwave/millimeter-wave radars [1]- [10] and high-frequency Lidars have been widely used in many important areas such as police car-speeding radars, auto-driving radars, Unmanned Aerial Vehicles (UAVs) navigation radars and remote heartbeat/respiration healthcare biomedical radars [7]- [10] *etc*. In particular, the long wavelength of the RF wave makes it ideal for long-range Doppler radar applications.

Conventional Doppler radars are either based on broadband pulse time-domain technique or Frequency Modulated Continuous Wave (FMCW) frequency-domain technique, which makes the radar architectures very complex and expensive. So it is desirable to develop a compact cost-effective consumer Doppler radars. Self-Injection Locked Oscillator based radars (SILO-Radar) are such Doppler radar architectures [2]. In this paper, we propose a compact SILO-Radar architecture at 5 GHz that consists of only a cross-coupled oscillator and a Schottky diode baseband detector, via the help of Hilbert transform.

II. THE SILO-RADAR

Fig. 1 shows the architecture of the SILO-Radar: it consists of a Voltage Controlled Oscillator a cross-coupled oscillator, which launches an outgoing wave through a patch antenna towards the Doppler object (a car here); then the outgoing wave is reflected by the Doppler object and is injected to the cross-coupled oscillator, changing the phase of the cross-couple oscillator $\phi(s = j\omega)$ as follows [2],

$$\phi(s) = \frac{\omega_{LR}\cos(\omega_{osc}\tau_D)}{s + \omega_{LR}\cos(\omega_{osc}\tau_D)\left(1 - e^{-s\tau_D}\right)}\phi_D(s), \qquad (1)$$

where $\phi_D(s)$ is the Laplace transform of the Doppler phase; τ_D is the round trip delay time between the antenna and the Doppler object; ω_{osc} is the angular frequency of the free running cross coupled oscillator; and ω_{LR} is the locking range of cross coupled oscillator.

The real part of the Doppler modulated phase signal $r(t)$ is then detected by a time-delay (τ) differential operator with a Schottky diode,

$$r(t) = \cos\left\{\omega_{osc}\tau + \phi(t+\tau) - \phi(t)\right\}, \qquad (2)$$

Then the detected real part signal $r(t)$ is sampled by an Analog-to-Digital Converter (ADC); and finally, a digital processor (e.g., an FPGA) is used to perform the Hilbert transform [64] to obtain the imaginary part of the Doppler modulated phase signal,

$$i(t) = \frac{1}{\pi t} \circledast r(t), \qquad (3)$$

where $\circledast$ denotes the convolution.

Now the Doppler modulated phase can be obtained from Eq. (2) and Eq. (3),

$$\omega_{osc}\tau + \phi(t) - \phi(t-\tau) = \arctan\left\{\frac{i(t)}{r(t)}\right\}, \qquad (4)$$

---

*Shaolin Liao is the corresponding author.

The work is partly supported by China Postdoctoral Science Foundation No. 2020M672488.

This preprint was submitted to 2020 Asia-Pacific Microwave Conference (APMC2020), which will be held in Hong Kong, SAR, P. R. China, December 8-11, 2020.

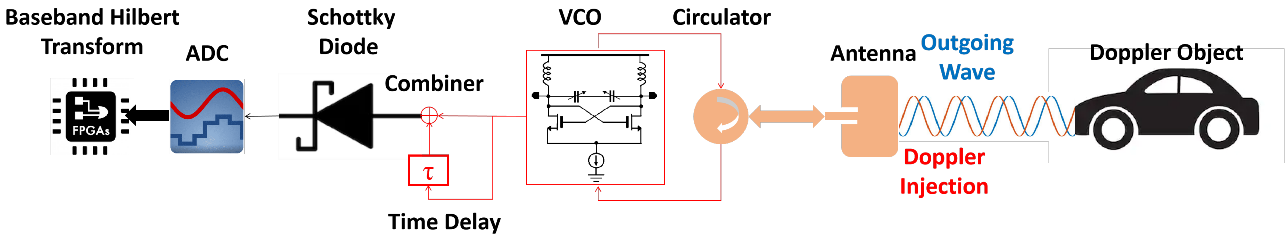


Fig. 1. Schematic of the SILO-Radar.

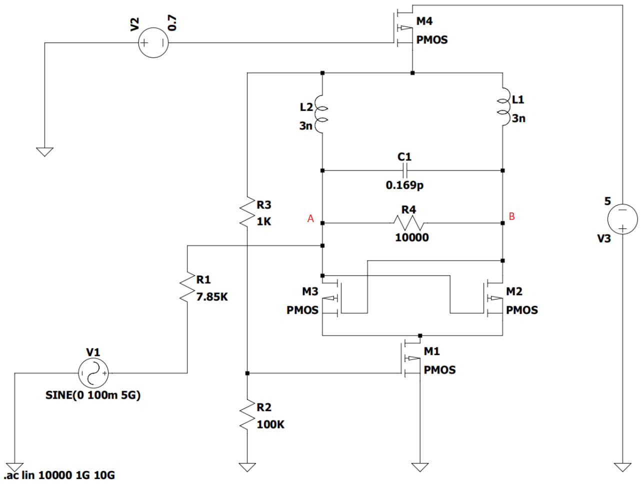


Fig. 2. The SILO circuit under study based on a cross coupled oscillator.

which can be solved through Laplace transform as follows,

$$\phi(s) = \frac{\mathcal{L}\left\{\arctan\left\{\frac{i(t)}{r(t)}\right\} - \omega_{osc}\tau\right\}}{1 - e^{-s\tau}}. \tag{5}$$

Finally, the Doppler phase can be obtained by substituting Eq. (5) into Eq. (1),

$$\phi_D(s) = H(s)\mathcal{L}\left\{\arctan\left\{\frac{i(t)}{r(t)}\right\} - \omega_{osc}\tau\right\}, \tag{6}$$
$$H(s) = \frac{s + \omega_{LR}\cos\left(\omega_{osc}\tau_D\right)\left(1 - e^{-s\tau_D}\right)}{\omega_{LR}\cos\left(\omega_{osc}\tau_D\right)\left(1 - e^{-s\tau}\right)}.$$

III. ANALYSIS AND SIMULATION OF THE SILO-RADAR

In this Section, we show the theoretical analysis of the cross coupled oscillator and the PSpice simulation of the SILO, whose circuit is shown in Fig. 2.

A. The Cross-Coupled Oscillator

The transfer function of the cross-coupled oscillator is given by,

$$H_{osc}(s) = \frac{s g_m L}{1 + s\frac{L(1 - g_m R_H)}{R_H} + s^2 LC}, \tag{7}$$

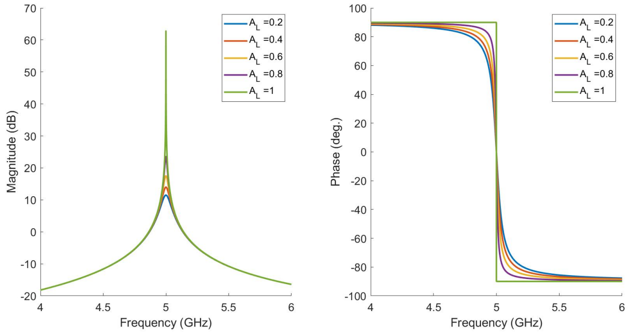


Fig. 3. The analytical transfer function of the cross-coupled oscillator: left) magnitude (dB); and right) phase (degree).

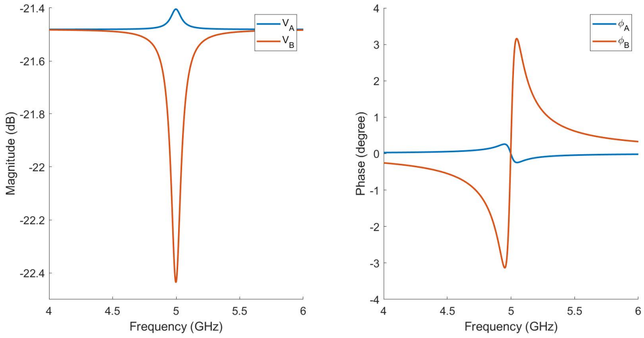


Fig. 4. The PSpice simulation of the transfer function of the cross-coupled oscillator at points A and B of Fig. 2: left) magnitude (dB); and right) phase (degree).

where g_m is the trans-conductance of the transistor of the cross-coupled oscillator; L, C and R_H are the inductance, the capacitance and the resistance of the half circuit.

The two poles of the transfer function H_{osc} of Eq. (7) are given by,

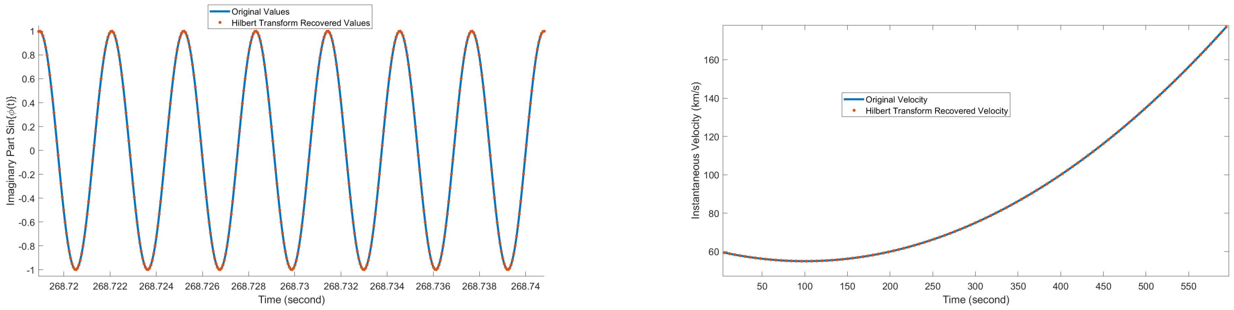
$$s_{1,2} = -\frac{1 - g_m R_H}{2R_H C} \pm j\sqrt{\frac{1}{LC} - \left(\frac{1 - g_m R_H}{2R_H C}\right)^2}. \tag{8}$$

From Eq. (8), it can be seen that the start-up condition for the cross coupled oscillator is given by,

$$g_m > \frac{\alpha}{R_H}, \tag{9}$$

where $\alpha \geq 1$ is required and usually $\alpha \geq 3$ is used to ensure the start-up of the cross coupled oscillator.

t



a) b)

Fig. 5. Doppler information recovered by the Hilbert transform: a) the recovered imaginary part sin $\{\phi(t)\}$; and b) the recovered Doppler velocity.

In particular, when $\alpha = 1$, the resonant frequency is calculated as follows according to Eq. (8),

$$\omega_{1,2} = \omega_{osc} = \sqrt{\frac{1}{LC}}. \tag{10}$$

On Fig. 3, we have plotted the magnitude and the phase of the transfer function given in Eq. (7), for the parameters of $L_1 = L_2 = L = 3$ nH, $C_1 = C/2$ 0.169 pF, $R_4 = 2R_H = 10000$ Ohm, and $g_m = 0.6$ mS. From Fig. 3, it can be seen that when the feedback amplitude $A_L = f g_m R_H$ approaches 1, *i.e.*, the feedback coefficient f approaches $1/(g_m R_H)$, Full Width at Half Maximum (FWHM) the resonant peak becomes narrower, meaning higher Q factor, which is given by $Q = 5$ GHz/FWHM.

B. PSpice Simulation of the SILO

We also performed the PSpice simulation of the SILO circuit shown in Fig. 2. The magnitude and phase plots for the output points of A and B of Fig. 2 have been shown in Fig. 4. Compared with the analytical transfer function of the cross coupled oscillator shown on Fig. 3, it can be seen that both the magnitude and phase behave similarly around the design frequency of 5 GHz.

C. Doppler Phase Recovered by the Hilbert Transform

To show the validity of Doppler phase recovery by the Hilbert transform, we have performed Hilbert transform for a car moving at the following velocity (in unit of km/hour),

$$v(t) = 60 + \frac{t^2}{20} + \frac{t^3}{6000}. \tag{11}$$

Fig. 5a) shows the imaginary part of the Doppler phase $\sin\{\phi(t)\}$ obtained from the Hilbert transform according to Eq. (3), and Fig. 5b) shows the recovered velocity. It can be seen that both the imaginary part of the Doppler phase and the recovered velocity agree well with their given original values, showing the feasibility of the Hilbert transform for Doppler information recovery.

IV. CONCLUSION

In this paper, we have studied a compact 5-GHz SILO-Radar that consists of only a cross-coupled oscillator and a Schottky diode baseband detector. The Doppler phase is extracted through the Hilbert transform at the baseband. Both analytical analysis and PSpice simulation have been performed to show the feasibility of the SILO-Radar. The SILO-Radar has the benefits of compactness, low-power consumption and low cost, enabling its use in many important consumer applications such as autonomous cars, UAVs, and remote heartbeat/respiration remote healthcare etc.

REFERENCES

[1] Thi Phuoc Van, N.; Tang, L.; Demir, V.; Hasan, S.F.; Duc Minh, N.; Mukhopadhyay, S. Review-Microwave Radar Sensing Systems for Search and Rescue Purposes. Sensors 2019, 19, 2879.

[2] F. Wang et al., "A Novel Vital-Sign Sensor Based on a Self-Injection-Locked Oscillator," in IEEE Transactions on Microwave Theory and Techniques, vol. 58, no. 12, pp. 4112-4120, Dec. 2010, doi: 10.1109/TMTT.2010.2087349.

[3] S. Liao, Z. Wang, L. Ou and Y. Peng, "A Harmonics Interferometric Doppler Sensor With a Neon Lamp Detector," in IEEE Sensors Journal, vol. 20, no. 10, pp. 5229-5236, 15 May15, 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, 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

[6] 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

[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. 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

[9] 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

[10] 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

[11] 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

[12] 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

[13] 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

[14] 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

[15] 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

[16] 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

[17] 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

[18] S. Liao, “Miter bend mirror design for corrugated waveguides,” *Letters of Progress in Electromagnetics Research*, vol. 10, pp. 157-162, 2009. DOI: 10.2528/PIERL09062103

[19] 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: 10.1163/156939307779367332

[20] 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

[21] 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

[22] 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

[23] 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

[24] 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

[25] 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

[26] 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

[27] S. Liao, “Validity of image theorem under spherical geometry,” *Progress in Electromagnetics Research Symposium (PIERS)*, Marrakesh, Morocco, 2011. arXiv:2007.02000: https://arxiv.org/abs/2007.02000

[28] 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

[29] 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

[30] 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

[31] 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, 2009. DOI: 10.1142/9789812814647 0068

[32] 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

[33] 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/PIERS060906005903

[34] 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

[35] 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 Teraherz Electronics*, Shanghai, 2006, pp. 260-260. DOI: 10.1109/ICIMW.2006.368468

[36] 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 Teraherz Electronics*, Shanghai, 2006, pp. 259-259. DOI: 10.1109/ICIMW.2006.368467

[37] 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

[38] 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

[39] 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

[40] 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.

[41] 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.

[42] 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

[43] 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.

[44] 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

[45] 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

[46] 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

[47] 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

[48] 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

[49] 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.

[50] 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.

[51] 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

[52] 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.

[53] 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

[54] S. Liao, T. Wong, and L. Ou, "Optimal feedback-interferometric fifer laser microphones," *Optics Letters, Optical Society of America (OSA)*, vol. 45, no. 2, pp. 423-426, Jan. 2020, DOI: 10.1364/OL.384225.

[55] 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.

[56] 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

[57] 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

[58] 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. Also available at arXiv.

[59] 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

[60] 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

[61] 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

[62] Y. He Y. Li Z. Zhou H. Li Y. Hou S. Liao and P. Chen, "Wide-band Epsilon-Near-Zero Supercoupling Control through Substrate-Integrated Impedance Surface," *Advanced Theory and Simulations*, vol. 2, no. 8, p. 1900059, 2019, DOI: 10.1002/adts.201900059.

[63] 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

[64] Zehra Saraç, H. Gülay Birkök, Ahmet Emir, and Ali Dursun "Phase recovery from interference fringes by Hilbert transform", Proc. SPIE 7443, Applications of Digital Image Processing XXXII, 74431I (2 September 2009); https://doi.org/10.1117/12.824866