Microwave Photonics Assisted by Machine Learning

Xiaoke Yi, Xiaoyi Tian, Luping Zhou, Liwei Li, Linh Nguyen, Robert Minasian

School of Electrical and Information Engineering, The University of Sydney, xiaoke.yi@sydney.edu.au

Abstract *The combination of machine learning with microwave photonics has provided advanced solutions that were previously unattainable. Recent advances are presented with a focus on using machine learning and deep learning techniques to assist microwave photonics in sensing with thermal interference mitigation and multi-parameter sensing capabilities.*

Introduction

Machine learning (ML), as a branch of artificial intelligence, has profoundly impacted diverse aspects of modern society, ranging from social media to healthcare, and provided new insights into biology, physics, medicine, and more [1-4]. Microwave photonics is a technology that combines microwave and optical signals to offer innovative solutions to a wide range of real-world challenges and has found applications in diverse fields, such as telecommunications, aerospace, and defence [5]. In recent years, ML and deep learning (DL) techniques have been increasingly incorporated into microwave photonic devices and systems, including sensing [6,7], photonic analog-to-digital conversion [8], filtering [9], and frequency measurement [10-12].

The increasing demand for sensors in modern life and the rapid development of technologies such as the Internet of Things and 5G/6G communications have led to the emergence of microwave photonic sensing as a highly promising research area. Microwave photonic sensors convert optical measurements to the microwave domain, enabling high-speed and high-resolution measurements using radio-frequency (RF) devices and technologies [6,7,13,14]. Microwave photonic sensors based on optical microresonators have the advantages of high sensitivity, compact size, massive production capability, and compatibility with other integrated devices. This makes them greatly suited for high-demand sensing applications, such as the detection of nanoparticles and biomolecules. As ML and DL are inherently adept at identifying patterns and performing complex predictions, it thus has great potential to enable higher performance for integrated microwave photonic sensors.

In this paper, we focus on ML-assisted microwave photonic sensing based on optical microresonators. We first introduce the operating principles and then present two different methods for incorporating the ML techniques in microwave photonic sensors to enable the athermal sensing capability. Next, we report a new paradigm of microwave photonic multi-parameter sensing enabled by DL and demonstrate simultaneous sensing of temperature and humidity by only using a single microresonator.

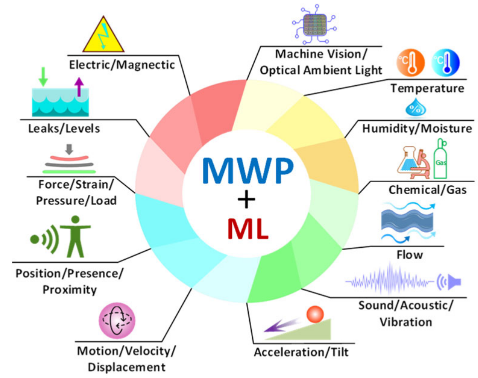

Fig. 1: The ML-assisted microwave photonics are of great potential boosting various sensing capabilities. MWP: Microwave photonics.

Principle of Microwave Photonic Sensing Based on Microresonators

When the external stimuli cause the disturbance of the optical mode that circulates in the optical cavity, the optical microresonators respond immediately in its optical transmission spectrum [15,16]. The responses are manifested in the resonance wavelength changes as well as changes in other characteristics of the resonance spectrum, such as the extinction ratio (ER) and full width at half maximum (FWHM). However, directly detecting those changes in the optical domain, for example, using the optical spectrum analyser, often has limited speed and resolution.

Microwave photonic techniques have been proposed to achieve high interrogation speed and resolution for optical microresonators [14,17-21]. Our proposed microwave photonic sensing system adopts the dual-drive Mach Zehnder modulator (DDMZM), which has two RF ports and one direct current (DC) bias port, to generate the interrogation light. The RF signals drive the two RF ports via a 90° electrical hybrid coupler. At the output of the DDMZM, there will be two first-order optical sidebands around the optical carrier, where the power and phase characteristics of the optical carrier and sidebands can be adjusted via the DC bias voltage. Based on the modulation characteristics of the DDMZM at different DC bias voltages and the phase transmission characteristics of the optical resonance at different coupling conditions, there always exists an optimal DC bias voltage that leads to a zero RF transmission point when one of the sidebands allocating at the resonance wavelength. By utilising this optimal DC bias voltage during the microwave photonic interrogation, any optical resonances, including those with a low quality factor and a small ER, can be transformed into an ultra-deep dip with a tiny tip width in the RF domain, which substantially improves the interrogation resolution while reducing the design and fabrication complexity. As the RF dip location corresponds to the resonance wavelength, the high-resolution microwave photonic sensing can thus be conducted by measuring the ultradeep RF dip in the interrogation output. Moreover, by adopting the linear-frequency modulated pulse which has a fast repetition rate as the RF modulation signals, the microwave photonic sensor can simultaneously achieve high sensitivity, high resolution, and high speed [19].

To compensate for the ER variation which affects the conditions required to create the zero-transmission point, we propose to incorporate the automatic correction of the optical sideband power via the feedback control of the DDMZM DC bias voltage into the microwave photonic interrogation scheme and demonstrate the humidity sensing via a microdisk resonator coated with hygroscopic material [20]. In [21], we further extend the auto-correction assisted microwave photonic sensing scheme to interrogate multiple resonances.

As a result of the point-to-point mapping mechanism in the microwave photonic interrogation, the RF dip at the interrogation output contains the entire range of information conveyed by the optical resonance spectrum within the interrogation range. This indicates the possibility of achieving the sensing of more than one parameter by exploiting the interrogation output of a single optical resonance. In the next sections, we will demonstrate the achievement of athermal microwave photonic sensing and microwave photonic multi-parameter sensing based on a single optical resonance by adopting the ML and DL techniques to exploit the microwave photonic interrogation output.

Athermal Microwave Photonic Sensors

The thermal effect is a critical factor that must be carefully considered in sensing, as temperature interference is often inevitable in practical situations and can have a significant impact on the accuracy and reliability of sensor measurements. The susceptibility of microresonators to temperature changes presents a great challenge for using them to detect other variables [21].

To achieve athermal sensing with microresonators, we present a new microwave photonic sensor scheme that employs the support vector regression (SVR) to compensate for the temperature variation-induced sensing errors [6]. The performance of the proposed microwave photonic sensor is evaluated via humidity sensing, where a silicon microdisk coated with hygroscopic material is used as the sensor probe. At a fixed temperature, the relative humidity (RH) level can be estimated based on the premeasured linear relationship between the RF dip locations and the RH levels. To maintain the validity of this linear equation in a temperature-varying environment, the SVR is trained with RF dip position and the DC bias voltage, which are extracted from the microwave photonic interrogation output collected under deviated temperature conditions, to generate the corrected RF dip position for accurate humidity estimation. In the experiment, 30 and 6 data are used to train and test the SVR model, respectively. Despite the limited dataset, the SVR-based correction model effectively eliminates the temperature-induced RF dip position drifts and guarantees a mean absolute error (MAE) of approximately 1.30% RH for humidity sensing at varied temperatures, which is more than 9-fold improvement compared to that using the linear equation without correction.

To remove the requirement for the reference linear estimation equation and the DC bias voltage for each microwave photonic interrogation output, we propose and investigate the approach of training the ML models with only the features extracted from the microwave photonic interrogation output to directly generate the estimation of the target measurand while accounting for thermal interference [7]. Similarly, we validate this approach in the humidity sensing experiment. After each microwave photonic interrogation, the RF dip position and average passband transmission are manually extracted from the microwave photonic interrogation output and combined as one data point. 36 data points labelled with the corresponding ground-truth RH levels are collected under different temperature and humidity conditions and used for training and testing two kernel-based ML methods, including the SVR and the neural tangent kernel (NTK), to build the athermal humidity estimation model in parallel for comparison. The SVR and NTK-based models all result in more than 2-fold improvement in accuracy compared to the conventional linear regression model, achieving lower MAEs of 1.29% RH and 1.01% RH, respectively.

Microwave Photonic Multi-parameter Sensing

To enable sensing more than one measurand without the requirement for complex design and fabrication of the sensor device, we present a new paradigm of microwave photonic multi-parameter sensing based on only a single resonance by employing DL techniques to exploit the full spectral information provided at the interrogation output [22].

Figure 2 shows the schematic diagram of the proposed DL-assisted microwave photonic sensor scheme, which is designed for simultaneous temperature and humidity sensing as a proof-of-concept. The scheme can be extended to sense other variables of interest. The response of the selected optical resonance to the changes in temperature and humidity is continuously transformed into the line-shape variations of the RF spectral dip via the microwave photonic interrogation. The DL model directly uses the raw RF spectra as input data without requiring any pre-processing. After being trained with the spectra acquired under diverse temperature and humidity conditions, the DL model can automatically identify and extract informative features from the microwave photonic interrogation output during the sensing process and use them to make accurate predictions of temperature and humidity levels. To mitigate the high demand for experimental data, we utilise the convolutional neural tangent kernel (CNTK) to develop the DL model, which approximates a convolutional neural network with infinite layer width but only has very few hyperparameters. The experimental dataset consists of 36 RF dip spectra obtained under six different temperatures and six different RH levels. Five rounds of 6-fold cross-validation using different initial permutations are conducted to ensure a comprehensive evaluation of the CNTK model. The estimation results are shown in Fig. 3. The median values of the estimated temperature and humidity levels exhibit good agreement with the corresponding ground truth values. Moreover, the total MAEs obtained from the five 6-fold cross-validations show a centralised distribution, with values of only 0.04 °C and 1.30% RH for temperature and humidity, respectively. Despite the limited size of the experimental dataset, these results provide compelling evidence for the feasibility of the proposed DL-assisted MWP multi-parameter sensing scheme.

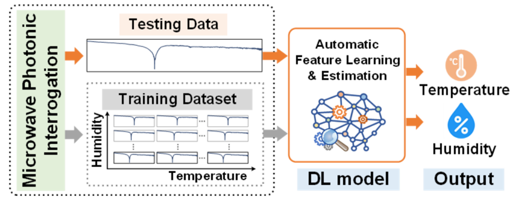

Fig. 2: The schematic diagram of the training and testing of the DL model for the simultaneous estimation of humidity and temperature by directly using the RF spectrum at the microwave photonic interrogation output.

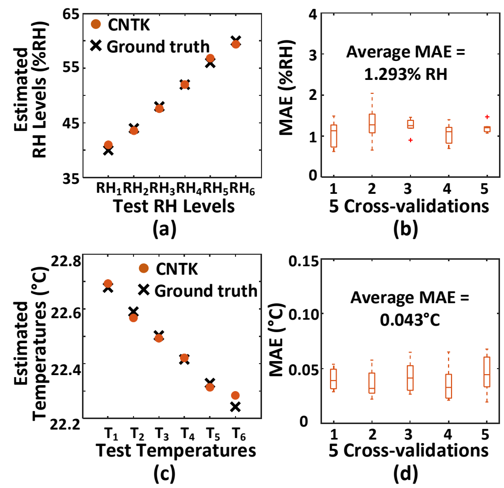

Fig. 3: The median values and MAE boxplots of the estimated (a) (b) RH levels and (c) (d) temperatures during the five 6-fold cross-validations, respectively.

Conclusions

In this paper, we present the recent advances in ML-assisted microwave photonic techniques, with a particular focus on the development of microwave photonic sensors. The incorporation of ML approaches into microwave photonic sensors shows significant potential for propelling the field of sensing forward, and unleashes new possibilities in various applications.

Acknowledgements

The work was supported in part by the Australian Research Council. Device fabrication and scanning electron microscopy were conducted at the Research and Prototype Foundry, a core research facility at the University of Sydney and a part of the Australian National Fabrication Facility. The authors would like to thank Y. Chen. and G. Gunawan for their valuable contributions to this work.

References

[1] M. I. Jordan and T. M. Mitchell, "Machine learning: Trends, perspectives, and prospects," *Science*, vol. 349, no. 6245, pp. 255-260, 2015, DOI: 10.1126/science.aaa8415.

[2] Y. LeCun, Y. Bengio, and G. Hinton, "Deep learning," *Nature*, vol. 521, no. 7553, pp. 436-444, 2015, DOI: 10.1038/nature14539.

[3] F. Musumeci, C. Rottondi, A. Nag, I. Macaluso, D. Zibar, M. Ruffini, and M. Tornatore, "An overview on application of machine learning techniques in optical networks," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 2, pp. 1383-1408, 2019, DOI: 10.1109/COMST.2018.2880039.

[4] A. Rajkomar, J. Dean, and I. Kohane, "Machine learning in medicine," *New England Journal of Medicine*, vol. 380, no. 14, pp. 1347-1358, 2019, DOI: 10.1056/NEJMra1814259.

[5] D. Marpaung, J. Yao, and J. Capmany, "Integrated microwave photonics," *Nature Photonics*, vol. 13, no. 2, pp. 80-90, 2019, DOI: 10.1038/s41566-018-0310-5.

[6] G. Gunawan, X. Tian, L. Zhou, L. Li, L. Nguyen, and X. Yi, "Machine learning assisted temperature insensitive microwave photonic sensor based on single microring resonance," in *IEEE International Topical Meeting on Microwave Photonics (MWP)*, 2021, pp. 1-4, DOI: 10.1109/MWP53341.2021.9639398.

[7] X. Tian, G. Gunawan, L. Zhou, L. Li, L. Nguyen, and X. Yi, "Athermal microwave photonic sensor based on single microring resonance by machine learning," *Journal of Lightwave Technology*, vol. 40, no. 20, pp. 6796-6804, 2022, DOI: 10.1109/JLT.2022.3209547.

[8] S. Xu, X. Zou, B. Ma, J. Chen, L. Yu, and W. Zou, "Deep-learning-powered photonic analog-to-digital conversion," *Light: Science & Applications*, vol. 8, no. 66, 2019, DOI: 10.1038/s41377-019-0176-4.

[9] R. -K. Shiu, Y. -W. Chen, P. -C Peng, J. Chiu, Q. Zhou, T. -L. Chang, S. Shen, J. -W. Li, and G. -K. Chang, "Performance enhancement of optical comb based microwave photonic filter by machine learning technique," *Journal of Lightwave Technology*, vol. 38, no. 19, pp. 5302-5310, 2020, DOI: 10.1109/JLT.2020.2989210.

[10] D. Shi, G. Li, Z. Jia, J. Wen, M. Li, N. Zhu, and W. Li, "Accuracy enhanced microwave frequency measurement based on the machine learning technique," *Optics Express*, vol. 29, no. 13, pp. 19515-19524, 2021, DOI: 10.1364/OE.429904.

[11] Y. Zhou, F. Zhang, J. Shi, and S. Pan, "Deep neural network-assisted high-accuracy microwave instantaneous frequency measurement with a photonic scanning receiver," *Optics Letters*, vol. 45, no. 11, pp. 3038-3041, 2020, DOI: 10.1364/OL.391883.

[12] Q. Liu, B. Gily, and M. P. Fok, "Adaptive photonic microwave instantaneous frequency estimation using machine learning," *IEEE Photonics Technology Letters*, vol. 33, no. 24, pp. 1511-1514, 2021, DOI: 10.1109/LPT.2021.3128867.

[13] J. Yao, "Microwave photonic sensors," *Journal of Lightwave Technology*, vol. 39, no. 12, pp. 3626-3637, 2021, DOI: 10.1109/JLT.2020.3047442.

[14] X. Tian, K. Powell, L. Li, S. X. Chew, X. Yi, L. Nguyen, and R. Minasian, "High resolution optical microresonator-based sensor enabled by microwave photonic sidebands processing," *Journal of Lightwave Technology*, vol. 38, no. 19, pp. 5440-5449, 2020, DOI: 10.1109/JLT.2020.3005218.

[15] L. Li, X. Tian, D. Meng, M. Collins, J. Wang, R. Patterson, L. Nguyen, and X. Yi, "Processing, characterisation, and impact of Nafion thin film on photonic nanowaveguides for humidity sensing," *Advanced Photonics Research*, vol. 3, no. 2, p. 2100181, 2022, DOI: 10.1002/adpr.202100181.

[16] W. Bogaerts, P. De Heyn, T. Van Vaerenbergh, K. De Vos, S. Kumar Selvaraja, T. Claes, P. Dumon, P. Bienstman. D. Van Thourhout, and R. Baets, "Silicon microring resonators," *Laser & Photonics Reviews*, vol. 6, no. 1, pp. 47-73, 2012, DOI: 10.1002/lpor.201100017.

[17] X. Tian, K. Powell, L. Li, S. X. Chew, X. Yi, L. Nguyen, and R. Minasian, "Silicon photonic microdisk sensor based on microwave photonic filtering technique," in *IEEE International Topical Meeting on Microwave Photonics (MWP)*, 2019, pp. 1-4, DOI: 10.1109/MWP.2019.889203.

[18] J. Wang, L. Li, Y. Wang, X. Tian, L. Nguyen, and X. Yi, "Photonic crystal microring resonator sensor based on narrowband microwave photonic filtering technique, " in *Conference on Lasers and Electro-Optics/Pacific Rim*, 2020, pp. C7F_3, DOI: 10.1364/CLEOPR.2020.C7F_3.

[19] X. Tian, L. Li, L. Nguyen, R. Minasian, and X. Yi, "Microwave photonic sensor based on optical sideband processing with linear frequency-modulated pulse," in *IEEE International Topical Meeting on Microwave Photonics (MWP)*, 2022, pp. 1-4, DOI: 10.1109/MWP54208.2022.9997605.

[20] X. Tian, L. Li, L. Nguyen, R. Minasian, and X. Yi, "Automatic correction assisted microwave photonic sensor system for resolution enhancement in humidity measurement," in *IEEE International Topical Meeting on Microwave Photonics (MWP)*, 2020, pp. 66-69, DOI: 10.23919/MWP48676.2020.9314371.

[21] X. Tian, L. Li, S. X. Chew, G. Gunawan, L. Nguyen, and X. Yi, "Cascaded optical microring resonator based auto-correction assisted high resolution microwave photonic sensor, " *Journal of Lightwave Technology*, vol. 39, no. 24, pp.7646-7655, 2021, DOI: 10.1109/JLT.2021.3095336.

[22] X. Tian, L. Zhou, L. Li, G. Gunawan, L. Nguyen, and X. Yi, "Deep learning assisted microwave photonic multi parameter sensing," *IEEE Journal of Selected Topics in Quantum Electronics*, (under review).