In-Package Additively Manufactured Sensors for Bend Prediction and Calibration of Flexible Phased Arrays and Flexible Hybrid Electronics

Xuanke He, Manos M. Tentzeris
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA
xhe53@gatech.edu

***Abstract*— An additively manufactured in-package flex sensor for accurate bending prediction of flexible phased arrays is introduced. The sensor design is thin, flexible and accurate and can be readily embedded within a flexible phased array/Flexible Hybrid Electronics(FHE) package. Additively manufactured flexible phased arrays can be easily integrated with this proposed sensor using an all additive process. A series of bending tests were performed to measure the accuracy of the bending prediction for a proof-of-concept phased array. Using the dataset collected, the sensor can achieve 90% accuracy in predicting the bend radius in both directions over the phased array plane. Using a 29 GHz 15x15 element phased array model, results in an 1.04 dB average gain error per missclassification and only 0.071 dB error in total as compared to 10.2 dB average gain error when using a non-calibrated equally phased array. This approach could be easily expanded to include multiple bend axis for larger arrays and flexible packages allowing for the accurate detection of non-radial, irregular bends.**

***Keywords*— Inkjet Printing, packaging, phased arrays**

I. Introduction

5G has already brought about a new wave of wireless communication technologies enabling not only higher data speeds but also enabling new wearable electronics, large scale smart cities, autonomous vehicles and many more applications. Suffice to say that 5G technologies will be needed to be placed everywhere in a variety of locations and environments. This is why flexible in-package phased arrays will play a critical role in the mass-scale implementation of 5G systems as they feature adaptive beamforming, allowing for the effective focus of wireless signals in particular directions while nulling out interferers in other directions as well as being lightweight.

However phased arrays are traditionally fabricated using PCB technologies making them bulky and not flexible or conformal, limiting their widespread use. Additive manufacturing, due to its inherent properties of high on-demand reconfigurability, low substrate thermal and physical shocks and low cost enables flexible, lightweight in-package phased arrays to be easily fabricated. Flexible arrays however, come with their own challenges, primarily in the form of phase error, which occurs between antenna elements when they are bent. This can be corrected on-the-fly if the shape of the array and the positions of the elements is accurately known. Additive manufacturing, specifically inkjet printing, enables smart sensor integration into the phased array package which allows for on-the-fly adaptive beamforming control and phase correction, thus significantly mitigating the effects of a bent array. The sensors need to seamlessly integrate within existing phased array packaging structure stackups; additionally, sensors needs to be fully packaged, without the need for external hardware, as this greatly enhances the portability and ease of use of flexible arrays.

Several works have demonstrated efforts for the accurate pattern prediction and calibration of bent phased arrays. Historically, phased array calibration can be achieved using mutual coupling techniques on a static antenna setup[1]. An additional demonstration with flexible phased arrays using mutual coupling has been shown in [2]. These methods require dedicated hardware to detect phase measurements and requires a strong near field coupling effect in order for them to work, something that is not desirable in practical phased arrays. A resistive measurement technique has been utilized in [3] which uses a flex sensor to determine. However this sensor is 1-dimensional and is multi-material, meaning that it can only sense bending in one direction and is difficult to integrate into a fully packaged system. Advanced image processing

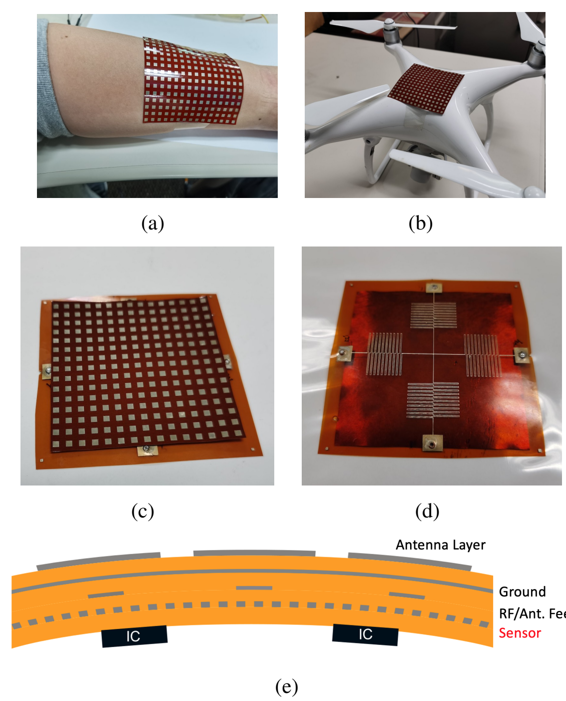
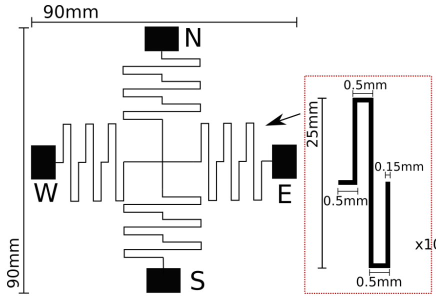
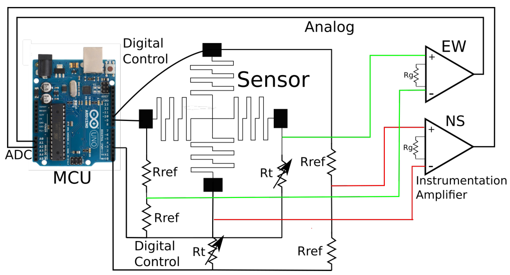


Fig. 1. Demonstration of applications of flexible phased array antenna which includes wearable technologies (b) and conformal structures. (c) Inkjet printed patch array with inkjet printed flex sensor (d). (e) Proposed layer stackup for a fully packaged flex sensor for flexible phased array calibration.

2021 IEEE/MTT-S International Microwave Symposium - IMS 2021 | 978-1-6654-0307-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/IMS19712.2021.9574896

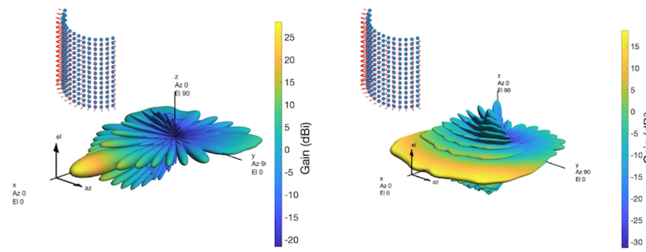


(a)

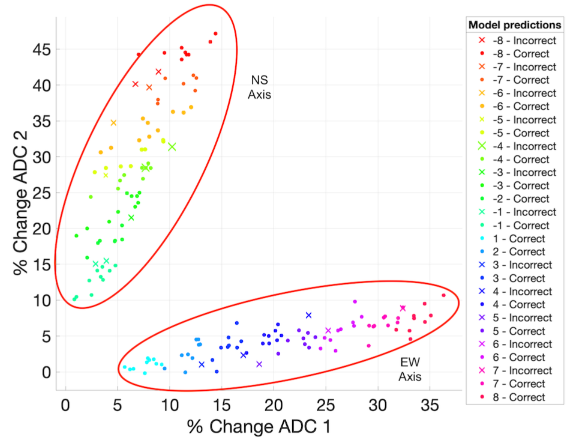


(b)

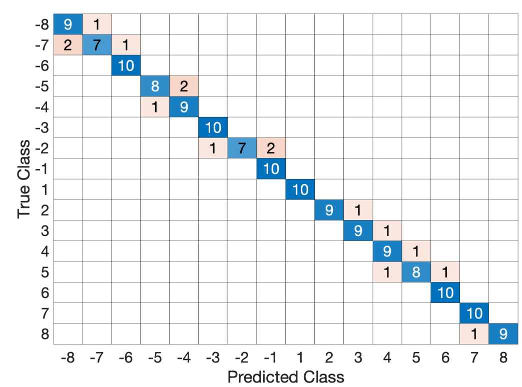
Fig. 2. (a) Sensor layout and dimensions. (b) Sensor measurement setup. Each axis of the sensor is placed into a Wheatstone bridge configuration, amplified and read by the MCU ADC.



(a)



(b)



(c)

Fig. 3. (a) Calibrated phased array using sensor data (right) vs uncalibrated equal phasing (left). (b) 160 data points collected, with false predictions marked as 'x'. The two groups shown are the two NS and EW bend axis measurements. (c) Confusion Matrix of the LDA model, which demonstrates that this is a good model as most of the predictions lie on the diagonal.

methods that measure bending also exist by using digital image correlation. However this involves using dedicated camera hardware and software processing making it not suitable for ubiquitous use [4].

In this work, a thin inkjet printed flex sensor for phased array calibration is fabricated and tested. It is printed on a thin flexible substrate allowing it to be easily integrated into a flexible package without negatively impacting flexible performance. A test methodology is developed which classifies the flexing output of the inkjet printed sensor and a proof-of-concept model of a 15x15 phased array is constructed and simulated. The flex sensor is measured at various bending radii, and the data acquired is used to train a model which adjusts the element excitation phase offsets based on the predicted bend radius. The designed sensor can sense strain in the two axii of the plane of the phased array, which are designated, which is designated North-South (NS) and East-West (EW), with a 90 percent accuracy calculated from 160 data points classified using Linear Discriminant Analysis (LDA), with all classification within +/- 1 class. Fig. 1 demonstrates various application areas that flexible phased arrays can be used along with the proposed stackup of the in-package sensor.

II. Inkjet Printed Flex Sensor

The inkjet printed proof-of-concept flex sensor dimensions are shown in Fig. 2(a). The ink is printed on 4 mil Kapton 500HN polyimide using SunChemical EMD5730 silver nanoparticle ink (SNP), sintered at 180C. The printed SNP changes its resistance based on the strain or flexing placed on the substrate. The line is meandered to increase the total line deformation distance leading to a greater change in resistance when flexed. The sensor is printed in a cross pattern to cover both axis, NS and EW, of bending. More dimensions can be added to sense local deformations in larger arrays. To measure the strain resistance accurately, the change in resistance needs to be placed into a Wheatstone-bridge configuration with the output voltage of the Wheatstone being the difference in voltage between the unknown strain resistance voltage divider and a known voltage divider. This difference is then amplified using an instrumentation amplifier and read using a Microcontroller Unit (MCU) demonstrated in Fig. 2(b). The gain of the instrumentation amplifier is set to approximately 165 making the voltage range of the measurements +/- 1 volt.

III. Testing and Validation

Due to the sensitivity of the sensor to minor flexing, and the need to acquire many data points quickly for training purposes, a systematic test structure was developed to characterize the flexing under test. A structure was developed which acts as a self clamp for the sensor under test. The sensor could be nudged back and forth from its current position and measurements could be taken rapidly while providing stable test results. Data is taken at 8 sequential notches which is equivalent to a bend radii of roughly 155, 80, 60, 50, 45, 40, 37.5 and 34.5mm. Each of these notches correspond to a class of bending with one axis. With two axis of bending, there is 16 distinct bend classes. The classes are labeled 1 to 8 for NS bend axis, -1 to -8 for EW bend axis for classification.

A total of 160 tests were performed generating 160 observations. These observations were divided equally among the two axis and 16 classes. Classification was performed by using discriminant analysis (LDA). The feature vectors used are the percent change, between resting and bent, in voltage readings for both outputs of the instrumentation amplifier, one for each axis. 5 fold cross validation was performed to measure the accuracy of the model. Correct bend prediction is necessary as shown in Fig. 3 (a), where the difference in gain between calibrated and uncalibrated arrays is over 10dB. The dataset collected is visualized in Fig. 3(b) and the confusion matrix is shown in Fig. 3(c). The confusion matrix demonstrates a good correlation between true class and predicted class, where most of the predictions reside along the main diagonal, with no predictions being two classes away.

IV. Bent Phased Array Calibration Results

A 15x15 conformal array setup using 29 GHz patch antenna elements spaced $\lambda/2$ apart was constructed using the Phased Array toolbox in MATLAB. A data vector, containing information on the percentage voltage change of both NS and EW axis, was collected from the sensor which is used in the LDA based prediction function. The LDA model predicts a class either -8 to -1 or 1 to 8, which was then translated into a specific bending radius on either NS or EW axis. A steering vector, which consisted of the relative phases of each individual element in the array, was calculated in MATLAB such that the array would point its main beam towards a constant direction normal to its broadside plane, in this case $\theta = \phi = 0$. To determine the efficiency of the proposed approach, the optimal (calibrated) radiation performance of the phased array for a specific ("true") bending radius ("class") has to be compared with the calibrated performance using the predicted class from the proposed sensor and the gain error due to potential misclassifications has to be quantified. Similar metrics (e.g. S21) can be defined for other packaged FHE configurations that require self-calibration due to bending. Using the dataset, we can determine the total cost which factors in gain error. The total gain error is defined in Eq. 1

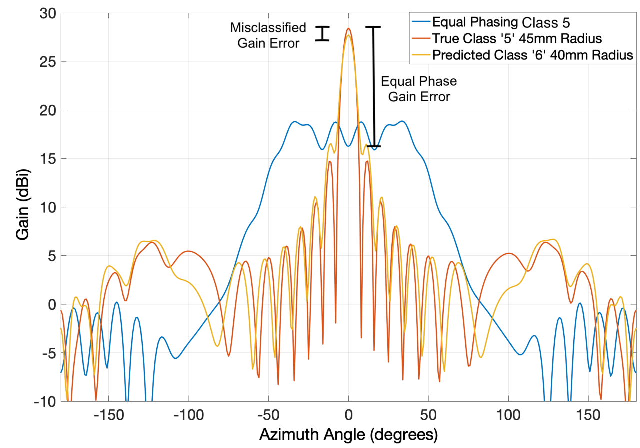


Fig. 4. Example case of a misclassification gain error. A class 5 bend was performed but was misclassified as class 6, thus the wrong steering vector was generated. The generated pattern (yellow) is the result of the incorrect steering vector applied to the array, while the desired pattern is in red. However, even though it was misclassified, the error is small compared to the error from an array with no calibration, equal phased feeding (blue) with a class 5 bending.

$$E = \frac{\sum_{k}^{N_f} \|G_{T,k}(\theta,\phi) - G_{F,k}(\theta,\phi)\|}{N_f} \quad (1)$$

where $G_{T,k}$ and $G_{F,k}$ is the true gain and the misclassified gain and N_f is the number of misclassifications using the LDA algorithm. An example case of misclassification is visualized in Fig. 4. The result of this error results in an average gain error cost of 1.04 dB per misclassification. In total, accounting for the entire dataset, the average gain error is only 0.071 dB. When compared with all equal phase feeding, the average gain error is 10.2 dB over the entire dataset.

V. Conclusion

This work demonstrates the versatile capability of additive manufacturing which can create embedded sensors in flexible phased array and FHE packages. An inkjet printed flex sensor was fabricated to predict bending and enable self-calibration by accurately correcting the phasing offsets for the deformation of the array with 90% accuracy, results in only 1.04 dB average gain error per missclassification and 0.071dB error in total for radii curvatures above 34.5mm.

References

[1] H. M. Aumann, A. J. Fenn, and F. G. Willwerth, "Phased array antenna calibration and pattern prediction using mutual coupling measurements," *IEEE Transactions on Antennas and Propagation*, vol. 37, no. 7, pp. 844–850, 1989.

[2] A. C. Fikes, A. Safaripour, F. Bohn, B. Abiri, and A. Hajimiri, "Flexible, conformal phased arrays with dynamic array shape self-calibration," in *2019 IEEE MTT-S International Microwave Symposium (IMS)*, 2019, pp. 1458–1461.

[3] B. D. Braaten, S. Roy, S. Nariyal, M. Al Aziz, N. F. Chamberlain, I. Irfanullah, M. T. Reich, and D. E. Anagnostou, "A self-adapting flexible (selflex) antenna array for changing conformal surface applications," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 2, pp. 655–665, 2013.

[4] B. Pan, K. Qian, H. Xie, and A. Asundi, "Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review," *Measurement Science and Technology*, vol. 20, no. 6, p. 062001, apr 2009.