Metasurface Enhanced Ultra-wideband Multifunctional Antenna Arrays and Fabry-Perot Antennas

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Certificate of Original Authorship

I, Alpha Osman Bah declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering and Information Technology at the University of Technology Sydney. This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This research is supported by the Australian Government Research Training Program, the Commonwealth Scientific and Industrial Research Organization (CSIRO), and the Cooperative Research Centre for Space Environment Management (SERC Limited) through the Australian Government's Cooperative Research Centre Programme.

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Thesis Format

The format of this Thesis is by compilation. The major contents of Chapter 2 are derived from a paper we published in *Scientific Reports* entitled, "Realization of an Ultra-thin Metasurface to Facilitate Wide Bandwidth, Wide Angle Beam Scanning." The major contents in Chapter 3 are derived from a paper we published in the *IEEE Transactions on Antennas and Propagation*, entitled "A Wideband Low-Profile Tightly Coupled Antenna Array with a Very High Figure of Merit." Chapter 3 is based on a paper we submitted to the *IEEE Transactions on Antennas and Propagation*, entitled “A Wideband Low-Profile Fabry-Perot Antenna Employing a Multi-Resonant Metasurface Based Superstrate.” The publication details of these Journal papers, and other Conference Proceeding Papers, Presentations, Posters, and Book Chapter that I have contributed towards are given in the next section.

Publications

Refereed Journal Articles

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[3] A. O. Bah, Y. J. Guo, P. Y. Qin and T. S. Bird, "A Wideband Low-Profile Fabry-Perot Antenna Employing a Multi-Resonant Metasurface Based Superstrate," *IEEE Trans. Antennas Propag*, Feb. 2019. (Submitted).

Book Chapters

[1] T. S. Bird, A. O. Bah, and K. Smart, "Measurement of Mutual Coupling Effects," in *Mutual Coupling Between Antennas*, John Wiley & Sons, West Sussex, UK. (In preparation).

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[2] A. O. Bah, P. Y. Qin, and T. S. Bird, "A Low Profile Antenna Array with a 5.6:1 Bandwidth for Multifunctional Applications," *16th Australian Symposium on Antennas (ASA2019),* Sydney, Australia, 2019. (Poster presentation)

[3] A. O. Bah, R. W. Ziolkowski, P. Qin, and Y. J. Guo, "Design and analysis of a wide angle impedance matching metasurface for wideband antenna arrays," *12th European Conference on Antennas and Propagation (EuCAP 2018)*, London, pp. 1-4, 2018.

[4] A. O. Bah, P. Y. Qin and Y. J. Guo, "A Wideband (5.6:1) Antenna Array with a Simple Low Profile Feed Structure," *International Symposium on Antennas and Propagation (ISAP 2018)*, Busan, South Korea, 2018. http://isap2018.org/download/program/ThB1.PDF

[5] A. O. Bah, Pei-Yuan Qin and Y. J. Guo, "An extremely wideband tapered balun for application in tightly coupled arrays," *2016 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, Cairns, QLD, pp. 162-165, 2016.

[6] X. Yang, G. Zhao, W. Hu, Y. J. Guo, Y. Z. Yin and A. O. Bah, "Characteristics of wideband phased array with two-layer metasurface," *2016 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Cairns, QLD, pp. 852-855, 2016.

[7] A. O. Bah, "Reconfigurable ultrawideband tightly coupled antenna arrays," *2016 Space Environment Research Centre (SERC) Colloquium*, Mount Stromlo, Canberra, 2016.

Abbreviations

AA	Aperture Arrays
A_{eff}	Effective Area
AMC	Artificial Magnetic Conductor
AMS	Aperture Type Metasurface
Apertif	Aperture Tile in Focus
ASKAP	Australian Square Kilometre Array Pathfinder
B	Balun
CA	Connected Array
CM	Common Mode
COTS	Commercial Off The Shelf
CPS	Coplanar Strip
CPW	Coplanar Waveguide
CSIRO	Commonwealth Scientific Industrial and Research Organisation
DBW	Directivity Bandwidth
DBWP	Directivity Bandwidth Product
DS	Double Sided
EBG	Electromagnetic Bandgap
EM	Electromagnetic
EMBRACE	Electronic Multibeam Radio Astronomy Concept
EW	Electronic Warfare
FOV	Field of View
FPA	Fabry-Perot Antenna
FSS	Frequency Selective Surface
GBW	Gain Bandwidth
GBWP	Gain Bandwidth Product
HFSS	High Frequency Structure Simulator
LFAA	Low Frequency Aperture Array
LOFAR	Low Frequency Array

MFAA	Mid Frequency Aperture Array
MS	Metasurface
MT	Meandered Transformer
MTM	Metamaterial
MVG	Microwave Vision Group
MWA	Murchison Widefield Array
NZI	Near Zero Index
P_A	Array Figure of Merit
PAF	Phased Array Feed
PCB	Printed Circuit Board
PCS	Phase Correcting Structure
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
PMS	Patch Type Metasurface
PRS	Partially Reflective Surface
PUMA	Planar Ultrawideband Modular Array
SB	Shorter Balun
SIW	Substrate Integrated Waveguide
SKA	Square Kilometre Array
SKA1-Low	Square Kilometre Array Phase-1 Low Frequency
SKA1-Mid	Square Kilometre Array Phase-1 Mid Frequency
SRR	Split Ring Resonator
SS	Single Sided
ST	Straight Transformer
TCAA	Tightly Coupled Antenna Array
TCDA-IB	Tightly Coupled Dipole Array with an Integrated Balun
TC-UAJC	Tightly Coupled Unequal Arm Jerusalem Cross
TE	Transverse Electric
TM	Transverse Magnetic
UCS	Uniform Current Sheet

UWB	Ultrawideband
VSWR	Voltage Standing Wave Ratio
WAIM	Wide Angle Impedance Matching

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Abstract

In recent years, the demand for ultra-wideband (UWB) antennas and arrays has escalated due to their flexibility and high data rate capabilities. This demand is driven by bandwidth intensive applications such as radio telescopes, satellite communications, and advanced radar systems. Wideband antennas enable the incorporation of multiple steerable beams, polarizations, and frequency bands onto a single multifunctional aperture.

Two of the main obstacles to truly multifunctional tightly coupled antenna arrays (TCAAs) is the problem of impedance mismatch at the aperture–air boundary and the need for a wideband and fully integrated feed network. The high cost and losses in the feed networks of TCAAs renders them impractical for some applications. In these cases, the low-cost and highly efficient Fabry-Perot antenna (FPA) provides a possible solution.

In the first part of this thesis, we present the design, analysis, and practical implementation of a 10x10 wideband TCAA with a very high figure of merit. The array figure of merit is a single number which takes into account the bandwidth, profile, polarization, scan range, and overall complexity of the array. An improved design of the fabricated array has a performance that approaches the fundamental limits of low profile arrays with a bandwidth of 5.5:1, a maximum scan range of 80° along the E-plane, and a profile of $\sim\lambda_L/12$. This excellent performance is enabled by a newly introduced feed network that is simple, inexpensive, and extremely wideband; in conjunction with a novel ultra-thin metasurface superstrate for wideband wide angle impedance matching.

The usual method of enhancing the gain bandwidth of FPAs involve the use of multi-layered superstrate structures which increase their profile and complexity. In the second part of this thesis, we develop a new approach to FPA gain bandwidth enhancement. Using this new approach, a small foot print, wideband, and low-profile FPA empowered by a single multi-resonant metasurface superstrate is designed, fabricated and tested. Due to the small foot print of this FPA, it can be easily employed as an element in an active array setting without the introduction of grating lobes. At the same time, the number

of active elements will be significantly reduced compared to the dense TCAAs leading to substantial cost reductions.