Electronically Tunable Coaxial Right / Left Handed Transmission Line for Carbon Fibre Reinforced Polymer Waveguides

Kelvin J. Nicholson
Aerospace Division
Defence Science and Technology Organisation
Melbourne, Australia
kelvin.nicholson@dsto.defence.gov.au

Jake Clough and Kamran Ghorbani
School of Electrical and Computer Engineering
RMIT University
Melbourne, Australia

***Abstract*— The Slotted Waveguide Antenna Stiffened Structure (SWASS) utilizes conventional carbon fiber reinforced polymer (CFRP) blade stiffeners in aircraft sandwich structures as microwave waveguides. Slotted waveguide antenna arrays may therefore be integrated into the CFRP structure by machining slots through the outer skin. This work presents a simple addition to the SWASS concept that permits electronic control over the propagating mode in a slotted CFRP waveguide for the purpose of beam steering. This is achieved using a varactor loaded coaxial composite right / left handed transmission line (CRLH-TL) with integrated bias circuit. The proposed CRLH-TL does not require a perfect electrical connection to the outer coaxial conductor and is therefore ideally suited to CFRP waveguides.**

Keywords*— *Transmission Lines, Composite Materials, Periodic Structures, Left Handed Circuits, Antenna Arrays.

I. INTRODUCTION

Slotted waveguide antennas date back to the 1940s [1] and are still in popular use today. Their mechanical robustness and simple construction favor a variety of applications across the maritime and aerospace domains. However, the increasing use of carbon fiber reinforced polymer (CFRP) has recently inspired the Slotted Waveguide Antenna Stiffened Structure (SWASS) concept [2] illustrated in Fig. 1.

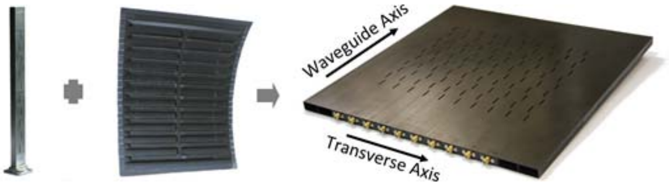


Fig. 1. The SWASS concept merges traditional slotted waveguide antennas with typical CFRP hat-stiffened aircraft panels.

The orientation of these waveguides is governed by the primary mechanical load applied to the structure. When multiple slotted waveguides are aligned as in Fig. 1, the radiation pattern is easily steered in the plane transverse to the waveguide axis by tuning the relative phase of each feed. To steer the radiation pattern in the plane parallel to the waveguide axis necessitates a method to advance or delay the propagating mode between consecutive radiating slots.

A method to achieve the required in-line phase shift was developed in [3] for metallic coaxial waveguides. Electronic control of the propagating mode in the waveguide was accomplished with a varactor loaded coaxial composite right / left handed transmission line (CRLH-TL). However, the transmission line in [3] necessitated a DC electrical connection with the coaxial outer conductor to ensure equal reverse bias across all varactors in the structure. Unfortunately, this method cannot be implemented in CFRP waveguides because of the encapsulating epoxy layer typical of aerospace composites. Hence, this work presents a new CRLH-TL design that incorporates the bias geometry within the coaxial CFRP outer conductor. No DC electrical connection to the CFRP outer conductor is therefore required to achieve both left and right handed propagation.

II. THEORY

The proposed CRLH-TL is illustrated in Fig. 2. A rectangular coaxial cross-section was chosen to fit with existing SWASS panels. The center conductor, shunt and bias lines are etched in copper on a 0.508 mm thick Rogers RT/duroid 5880 substrate suspended about the mid plane of the rectangular outer conductor. Lumped circuit elements are used to model the varactors, inductors and resistors.

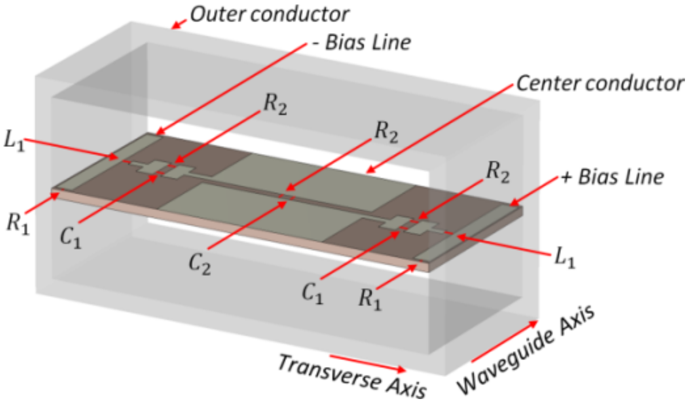


Fig. 2. The proposed unit cell of the coaxial CRLH-TL with lumped varactors (C_1 and C_2), inductors (L_1) and resistors (R_1 and R_2).

If the proposed CRLH-TL unit cell in Fig. 2 is concatenated such that every second unit cell is mirrored, a single DC bias may be used to tune each varactor. The resistors R_1 = 10.0 kΩ between each unit cell prevent the onset of a coaxial mode propagating along the bias lines. The resistors R_2 = 10.0 MΩ in parallel with each varactor (C_1 and C_2) ensures equal division of the bias voltage throughout the unit cell. Provided the ratio R_1:R_2 is sufficiently small, all varactors in the proposed CRLH-TL structure receive approximately the same reverse bias voltage. For example, the equivalent DC bias circuit for the proposed CRLH-TL with four unit cells is illustrated in Fig. 3.

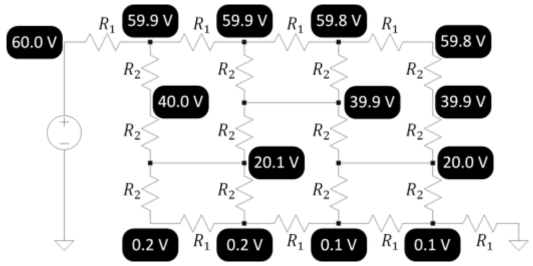


Fig. 3. Equivalent DC bias circuit for four units of the proposed CRLH-TL structure with R_1 = 10.0 kΩ and R_2 = 10.0 MΩ.

The reverse bias across each varactor (in parallel with R_2) differ by at most 0.1 V. This equates to a capacitance difference of less than 0.01 pF assuming a hyperabrupt varactor profile. This capacitance difference results in a slight blurring of the left and right pass bands that is deemed acceptable given only the net phase advance or delay at the design frequency is required for beam steering in the SWASS concept.

The theoretical dispersion diagram for the proposed transmission line (assuming identical varactor capacitances) may be calculated according to the method developed in [4]. For this work, the outer conductor has the cross-section dimensions of a standard WR-90 waveguide (22.86 mm along the transverse axis by 10.16 mm high) with a unit cell measuring d = 10.0 mm along the waveguide axis. The center conductor is 10.0 mm wide with 0.5 mm wide shunt lines. There is a 0.2 mm gap between the bias lines and waveguide short walls. This gap is necessary to isolate the bias lines from the outer conductor while also providing a small capacitance in series with the shunt varactors. The theoretical dispersion diagram for this geometry is presented in Fig. 4 when $C_1 = C_2$ is tuned from 0.2 pF to 0.4 pF with L_1 = 4.7 nH.

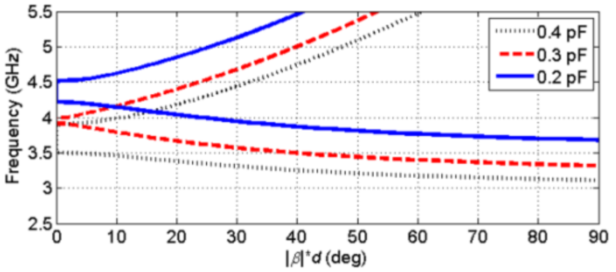


Fig. 4. Theoretical dispersion when $C_1 = C_2$ is tuned.

Careful selection of the inductance L_1 = 4.7 nH together with the 0.2 mm gap between bias lines and outer conductor ensures that the dispersion diagram is matched at the design frequency of 4.0 GHz when $C_1 = C_2$ = 0.3 pF. As the varactors are tuned, a stop band appears either side of this design frequency. However, at 4.0 GHz a propagating mode is always present. This mode can be used to achieve the necessary phase advance or delay between consecutive radiating slots. A different value for L_1 or a slight error in the gap between the bias line and outer conductor would not have yielded the same matched condition at the design frequency.

To validate the theoretical dispersion diagram, four units of the proposed CRLH-TL were simulated in the electromagnetic software package CST. For simplicity, the outer conductor was modelled as a perfect electrical conductor (PEC). The complex CFRP conductivity [5] was not used in the simulation to minimize the computational workload. The simulated S-parameters are presented in Fig. 5.

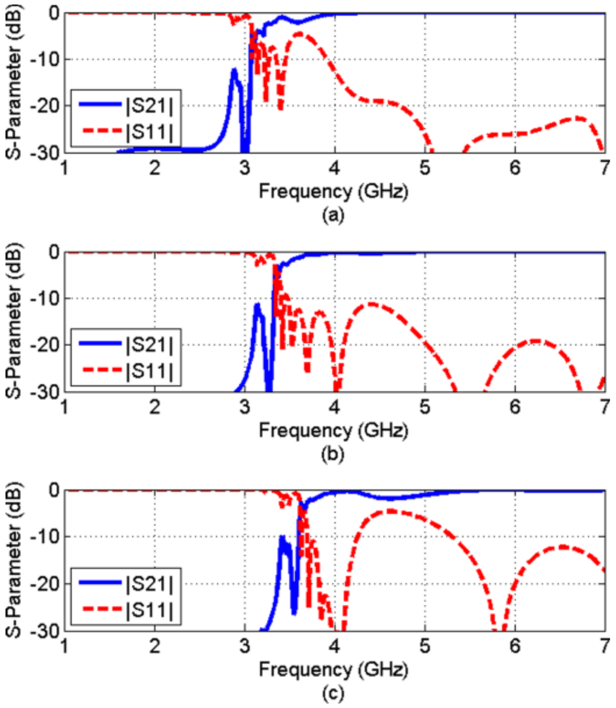
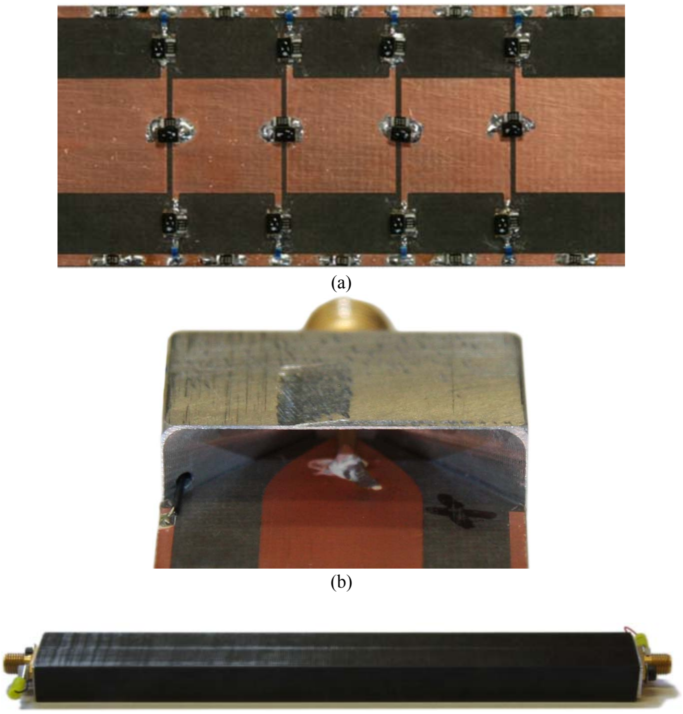


Fig. 5. Simulated S-parameters (assuming PEC) when $C_1 = C_2$ is tuned to (a) 0.4 pF, (b) 0.3 pF and (c) 0.2 pF.

As evident in Fig. 5, the proposed CRLH-TL is well matched when $C_1 = C_2$ = 0.3 pF with the left handed mode extending from approximately 3.3 GHz. Similarly, the onset of the left handed mode is evident at 3.1 GHz (when $C_1 = C_2$ = 0.4 pF) and 3.6 GHz (when $C_1 = C_2$ = 0.2 pF) in agreement with the theoretical dispersion diagram in Fig. 4. However, the predicted stop bands are only just evident in Fig. 5 (a) and (c) since only four units of the CRLH-TL were included in the simulation. More unit cells would enhance the stop band characteristic.

III. EXPERIMENT

Four unit cells of the proposed coaxial CRLH-TL were fabricated as illustrated in Fig. 6 (a) and installed in the CFRP outer conductor as illustrated in Fig. 6 (c). The MGV-125-08-0805 varactor (manufactured by Aeroflex Metelics) was used to implement C_1 and C_2. The inductor LQW15AN4N7B00D (manufactured by Murata) was used to implement L_1. The 10.0 kΩ resistor CPF0603B10KE (by Tyco Electronics) was used to implement R_1 and the 10.0 MΩ resistor CRCW060310M0F (by Vishay) was used to implement R_2.


(a)

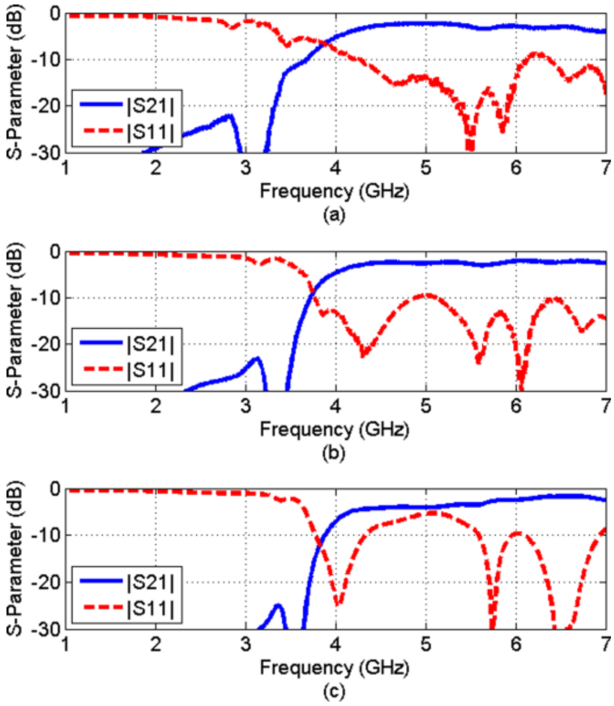
(b)

(c)

Fig. 6. Manufactured CRLH-TL structure (a) circuit geometry (b) tapered transition with bias ground and (c) installed in CFRP outer conductor to form the coaxial CRLH-TL.

The substrate was adhered to a section of Rohacell HF foam using commercial cyanoacrylate and was then installed in the outer conductor manufactured from CFRP according to the method described in [6]. To excite the quasi-TEM mode in the manufactured CFRP structure, a simple tapered transition from SMA to the rectangular coaxial waveguide was machined from aluminum as illustrated in Fig 6 (b). The bias wires were connected through 1.0 mm diameter holes in the aluminum feed transitions at either end of the CFRP waveguide.

The measured S-parameters in Fig. 7 demonstrate reasonable agreement with the simulated results in Fig. 5 albeit with approximately 2.0 dB more attenuation. This attenuation is attributed to the complex conductivity of the CFRP outer conductor [5]. However, for the intended SWASS application, only the net phase advance or delay is required for beam steering.



(a)

(b)

(c)

Fig. 7. Measured S-parameters for a total revers bias voltage of (a) 12.0 V (equivalent to 0.4 pF per varactor), (b) 24.0 V (equivalent to 0.3 pF per varactor) and (c) 60.0 V (equivalent to 0.2 pF per varactor).

The dispersion diagram may be approximated from the measured S21 phase according to the method in [4]. Although the measured dispersion in Fig. 8 qualitatively agrees with the theoretical dispersion in Fig. 4, no stop bands were observed because only four unit cells were fabricated. More unit cells would enhance the stop band characteristic. Regardless, the manufactured CRLH-TL operates as expected without the need to metallize the CFRP outer conductor. Hence, at the design frequency of 4.0 GHz, the propagating mode may be continuously tuned from left handed to right handed using a single DC bias.

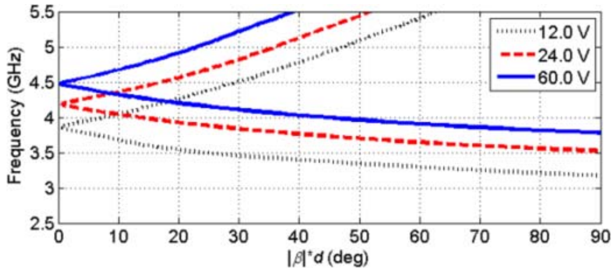


Fig. 8. Measured dispersion for four units of the CRLH-TL circuit in a CFRP outer conductor.

IV. CONCLUSION

This paper has presented a simple addition to the SWASS concept that permits electronic control of the propagating mode in a coaxial CFRP waveguide structure. The proposed coaxial CRLH-TL may be tuned with a single DC bias and does not require a DC electrical connection to the CFRP outer conductor. Hence, it is now possible to achieve the necessary phase advance or delay required for electronic beam steering in the SWASS concept. Manufacture of a complete CFRP slotted waveguide array incorporating the CRLH-TL is underway with results to be presented at the conference.

REFERENCES

[1] A. F. Stevenson, 'Theory of slots in rectangular wave-guides', J. Appl. Phys., vol. 19, no. 1, p. 24, 1948.

[2] P. J. Callus, 'Novel concepts for conformal load-bearing antenna structure', DSTO, Technical Report DSTO-TR-2096, 2008.

[3] K. Nicholson, W. S. T. Rowe, P. J. Callus, K. Ghorbani and T. Itoh, 'Coaxial Right / Left Handed Transmission Line for Electronic Beam Steering in the Slotted Waveguide Antenna stiffened Structure', *IEEE Trans. Microwave Theory and Techniques*, vol. 62, no. 4, pp. 773 – 778, 2014.

[4] C. Caloz and T. Itoh, Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications, NY, Wiley, 2005.

[5] A. Bojovschi, K. J. Nicholson, A. Galehdar, P. J. Callus, and K. Ghorbani, 'The Role of Fibre Orientation on the Electromagnetic Performance of Waveguides Manufactured from Carbon Fibre Reinforced Plastic', *PIER*, vol. 39, pp. 267–280, 2012.

[6] P. J. Callus and K. J. Nicholson, 'Standard Operating Procedure - Manufacture of Carbon Fibre Reinforced Plastic Waveguides and Slotted Waveguide Antennas - Version 1.0', DSTO, Technical Report DSTO-TR-0937, 2011.