Narrow-wall confined slotted waveguide structural antennas for small multi-rotor UAV

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***Abstract-* In preparation for a cross-discipline study of slotted waveguide antennas to be used as the load-bearing rods connecting the motor units to the central hub of a multi-rotor unmanned aerial vehicle, past work on carbon fiber reinforced plastic slotted waveguide is reviewed, and a novel narrow wall slot design is presented. The new slot is a distorted Z-shape which fits entirely within the narrow wall, and consequently does not require cutting of the corners of the rectangular tube which would significantly weaken the structure. The Z-slot was used in a 10-slot 15dBi antenna for 10GHz, which was shown to have comparable gain and return loss performance to a conventional narrow wall slotted waveguide antenna.**

I. Introduction

Small multi-rotor "helicopter" unmanned aerial vehicles (UAVs) are self-stabilizing flying platforms capable of hovering or low speed flight for periods of up to 40 minutes. These flight characteristics make these small UAVs perfect for high quality photography, such as for real estate. To date, these small UAVs have not been used for radio frequency applications, possibly due to the limited endurance. However, in an educational context where restricted flight time is not an operational impediment, these small UAVs are attractive for student projects on radio frequency sensing and radar; students are engaged by been able to interact with an actual UAV and likewise find the opportunity to work on a system to be integrated with the UAV exciting. Commercially available small mass Ultra-WideBand (UWB) and X-band FMCW radar units make radio frequency systems and machine vision projects possible for undergraduate students.

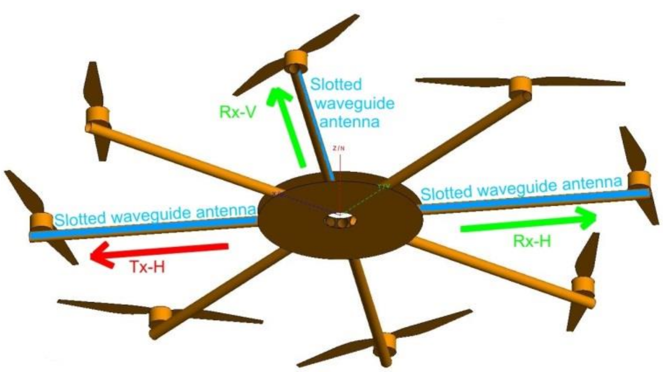

Figure 1. Multi-rotor unmanned aerial vehicle, with possible transmit (Tx) and receive (Rx) polarizations marked; diameter approximately 1 metre.

Applications such as radiometry, synthetic aperture radar (SAR) and ground moving target indicator (GMTI) require high gain antennas. While a means of using the full circular aperture of a 1 meter diameter multi-rotor UAV for a downward facing antenna is far from clear, a first practical step is to use the booms connecting the motor-propeller units to the central hub as antennas, Figure 1. Structural antennas are one approach to implementing high gain antennas without significantly adding to the weight or aerodynamic drag of an aircraft [1].

The main load-bearing structure of multi-rotor UAVs are hollow Carbon Fiber Reinforced Plastic (CFRP) tubes which connect the central box (housing sensors, battery and controller) to the outlaying electric motors and propellers, Figure 1. The hollow composite material tubes are roughly the same dimensions as X-band rectangular and circular waveguide, suggesting that slotted waveguide antennas can be used as arms without changing the design of an existing multi-rotor UAV nor adding to the mass. For the benefit of adding radio application without reducing flight endurance, there is the cost of weakening the booms by cutting the radiating slots.

The aim of this initial work was to produce a series of equivalent 10GHz 15dBi slotted waveguide antenna designs, which will be tested for deformation and instability in the future in a similar fashion to [1]. Attention was paid to the minimum slot-end to slot-end distance which is assumed to relate to maximum mechanical strength. In the following section, prior work on broad-wall slotted waveguide antennas made from CFRP is reviewed, with consideration given to the distance between the slot-ends. Narrow-wall slotted waveguide antennas are then considered, and a novel slot design discussed.

II. Prior Work On Broad-Wall Slotted Waveguide

As part of a project to integrate large aperture antennas into the load bearing structures on a fixed wing aircraft, a series of dry-layup CFRP rectangular slotted waveguide antennas were designed, built and tested for 9.375GHz Ground Moving Target Indicator or airborne weather radar [2]. For the layup of the CFRP WR-90 sized tubes, prepreg tape was wrapped around Teflon coated mandrels which were removed after curing [3]. This was a successful partial repeat of some historical work [4, 5].

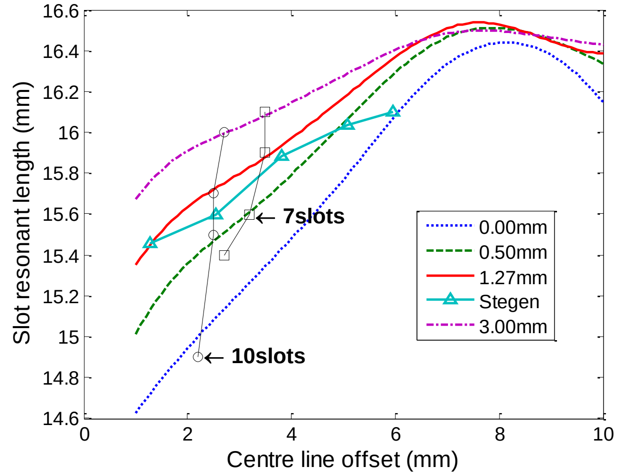

Figure 2. Single longitudinal broad-wall slot resonant length dependence on offset distance from broad-wall centre line at 9.375GHz for different waveguide wall thicknesses; derived from Figure 3 of [2], "Stegen" trace is experimental data taken from [6], with 7 and 10 slot antenna designs, from FEKO™.

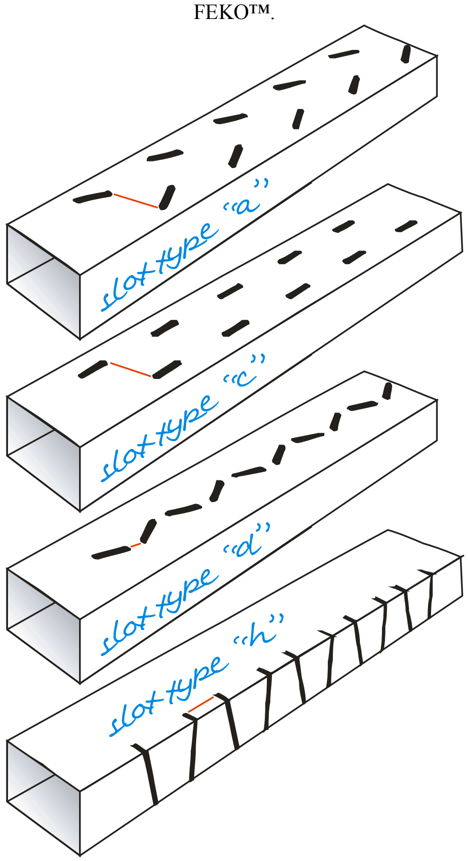

Figure 3. Sketches of WR-90 slotted waveguide antennas, based on Figure 9-2 of [6]; red line indicating minimum slot-end to slot-end distance.

As the aim of this work was to produce a series of slotted waveguide designs which will later be tested as load-bearing beams, the 9.375GHz 7-slot and 10-slot slotted waveguide design work of [2] was extended to include infinitely thin walled WR-90 waveguide, Figure 3. The "0.00mm" wall thickness results from FEKO™ were in agreement with the trend from the other wall thicknesses. For 10-slot antennas, the broad-wall center line offset remained at 2.1mm with the only difference been a shortening of the resonant slot length, Figure 2.

With FEKO™ simulations of infinitely thin walled 10-slot slotted waveguide antennas having proven to be quick and convenient of getting indicative antenna designs, the guided wavelength was changed to 39.7mm (10GHz) and a series of designs produced to gauge the maximum slot-end to slot-end distance, which was assumed to give maximum mechanical strength.

It is noted in [7] that longitudinal slots in the broad-wall of rectangular waveguide can be offset and parallel to the center line (type "c"), centered and rotated (type "d") or offset and rotated (type "a"), Figure 3. Examples of all 3 were designed in FEKO™ for 10GHz using 1.6mm width slots, Table 1. Both rotated slot designs had maximum cross-polarized radiation at 15.5dB below peak. The centered and rotated design gave the smallest slot-end to slot-end distance, and is considered a mechanical worst case; the array of slots look like a zipper-tear line. In contrast, the offset and rotated design gave an increased slot-end to slot-end distance. The 3 designs will be mechanically tested in the future and the effect of decreased slot-end to slot-end on weakening the rectangular waveguide tubes noted.

TABLE I
10GHz 10-Slot Broad-Wall Slotted Waveguide Antennas

Slot type	Slot length (mm)	Center line offset (mm)	Slot angle to center line (°)	Minimum distance (mm)
a	13.1	3.5	12.5	10.0
c	13.7	2.5	0	8.0
d	13.7	0	15	6.6

III. Narrow-Wall Slotted Waveguide

Having found that a less common broad-wall slotted waveguide antenna design gave increased slot-end to slot-end distance, and presumably increased mechanical strength, narrow wall type "h" slotted waveguide designs were investigated. As structural beams for a multi-rotor UAV, narrow-wall slotted waveguide antennas are preferred as a lesser cross-section is presented to the primary flight air flow from the propellers giving minimal drag as well as least bending moment. Four different waveguide wall thicknesses were used, Table 2. It is assumed that wall thicknesses approaching 3.00mm will be needed for mechanical strength.

TABLE II
Wall Thicknesses for WR-90 Slotted Waveguide Antennas

Wall thickness (mm)	Description
0.00	aluminum or brass foil inner layer of non-conductive fiber reinforced plastic tube
0.50	4-ply Carbon Fiber Reinforced Plastic (CFRP) dry layup as per [2]
1.27	standard WR-90 wall thickness for aluminum or copper waveguide
3.00	approximate face sheet or aircraft CFRP panel thickness

TABLE III
10GHz 10-Slot Narrow-Wall Slotted Waveguide Antennas

Wall thickness (mm)	Slot angle (°)	Slot extension (mm)	Minimum distance (mm)
0.00	17.8	2.4	14.5
0.50	19.0	2.2	14.2
1.27	17.5	1.8	14.6
3.00	21.7	0.6	13.7

TABLE IV
10GHz 10-Slot Z-Slot Slotted Waveguide Antennas

Wall thickness (mm)	Transverse dimension (mm)	Longitudinal dimension (mm)	Offset (mm)	Minimum distance (mm)
0.00	9.6	6.9	1.7	11.1
0.50	9.6	6.6	1.6	11.4
1.27	9.6	6.4	1.5	11.7
3.00	9.6	5.9	1.1	11.7

Past work on narrow-wall slots appears to have been restricted to maximum slot angles of 15° [7, 8], Figure 4A. Here, slot angles of 17.5° to 22° were found to be best, designs for all 4 wall thicknesses giving satisfactory return loss, Table 3 and Figure 5A. The radiation pattern characteristics of all 3 designs were likewise satisfactory, with around 15.5dBi directivity across the useful bandwidth of 9.8 to 10.1GHz, although the peak cross-polarized component increased with wall thickness, Figures 6A to 8A. The 8.5dB peak cross-polarized component of the 3.00mm wall thickness design here is unacceptably high, Figure 7A.

From a mechanical stand-point, the minimum slot-end to slot-end distances around 14.5mm were significantly better than the broad-wall designs, been a 45% increase in that dimension, Tables 1 and 3. Despite this improvement over the best broad-wall design, albeit at the cost of increased cross-polarization, the narrow wall slots do cut 2 corners of the rectangular waveguide. With the results of [1] in mind, cutting the corners of the waveguide is expected to significantly increase the susceptibility of the rectangular waveguide to both deformation and instability. Consequently, a slot design that is entirely confined to the narrow-wall was sort.

Considering the fundamental mechanism behind radiation from narrow wall slots, the slots sit at an angle to the narrow-wall currents, the angled current flow caused by a slot could be thought of as a "vector sum" of both longitudinal and transverse currents. Offsetting the ends of a square Z-slot was found to produce the required disturbance to the narrow wall currents, Figure 4B. A set of 4 designs was prepared for different wall thicknesses at 10GHz with the maximum transverse dimension been fixed at 9.6mm, Table 4. The return loss and radiation characteristics of the Z-slot antennas were satisfactory across the 9.8 to 10.1GHz band, Figures 5B to 8B. Comparing to the conventional narrow wall slot design, the cross-polarized component was noticeably lower, Figures 7 and 8. The only potential disadvantage been the lesser minimum slot-end to slot-end distance around 11.5mm, which, however, is an improvement over the original broad-wall designs, Tables 1 and 4.

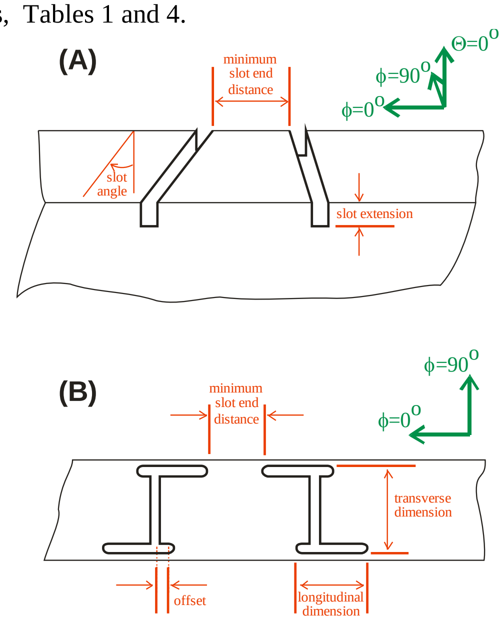

Figure 4. Sketches of slot pairs of narrow-wall slotted waveguide antenna; (A) conventional "h type" slots, (B) Z-slots.

IV. Conclusions

A series of 10GHz 15dBi slotted waveguide antennas were designed in the commercially available simulator FEKO™, which will be tested as load bearing beams in the future. In order to avoid corner-cutting in narrow-wall slotted waveguide antennas, a Z-slot that was confined within the narrow wall was designed, without loss of performance.

Acknowledgement

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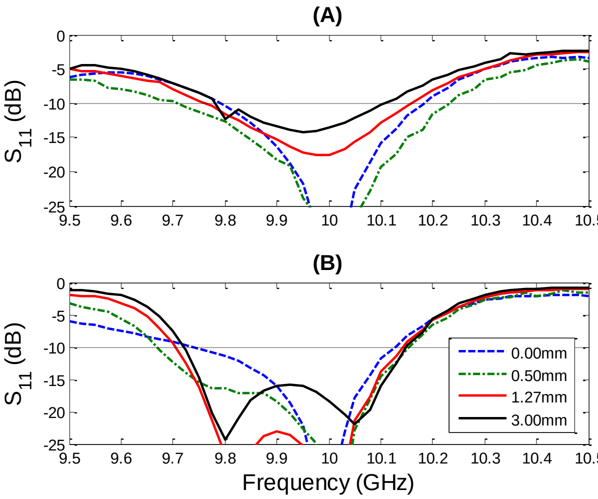

Figure 5. Return loss of 10 slot narrow-wall slotted WR-90 waveguide antennas designs, from FEKO™; (A) conventional slots, (B) Z-slots.

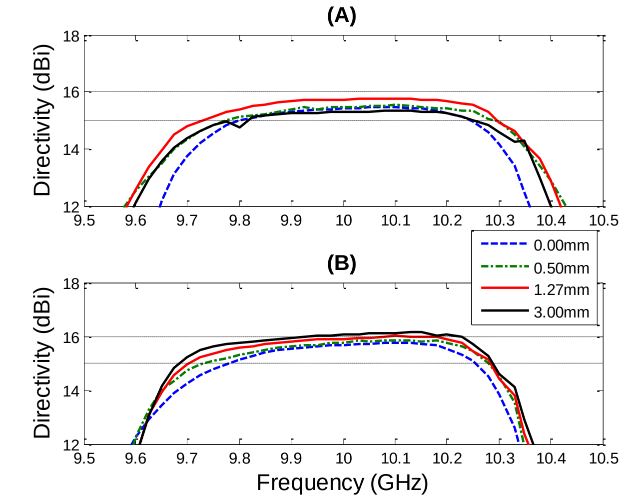

Figure 6. Directivity of 10 slot narrow-wall slotted WR-90 waveguide antennas, from FEKO™; (A) conventional slots, (B) Z-slots.

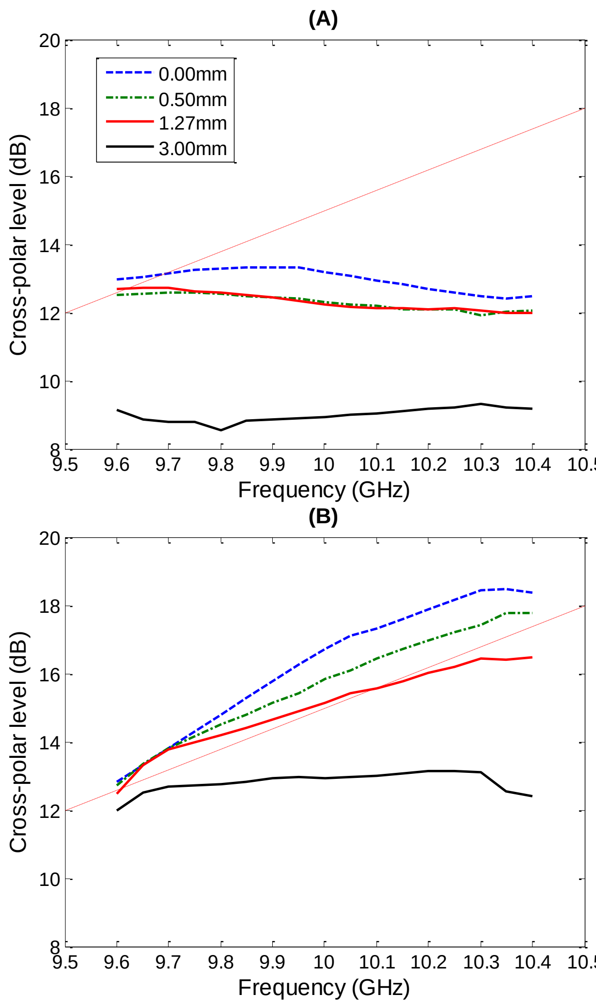

Figure 7. Peak cross-polarized component of radiation patterns of 10 slot narrow-wall slotted WR-90 waveguide antennas, from FEKO™; (A) conventional slots, (B) Z-slots..

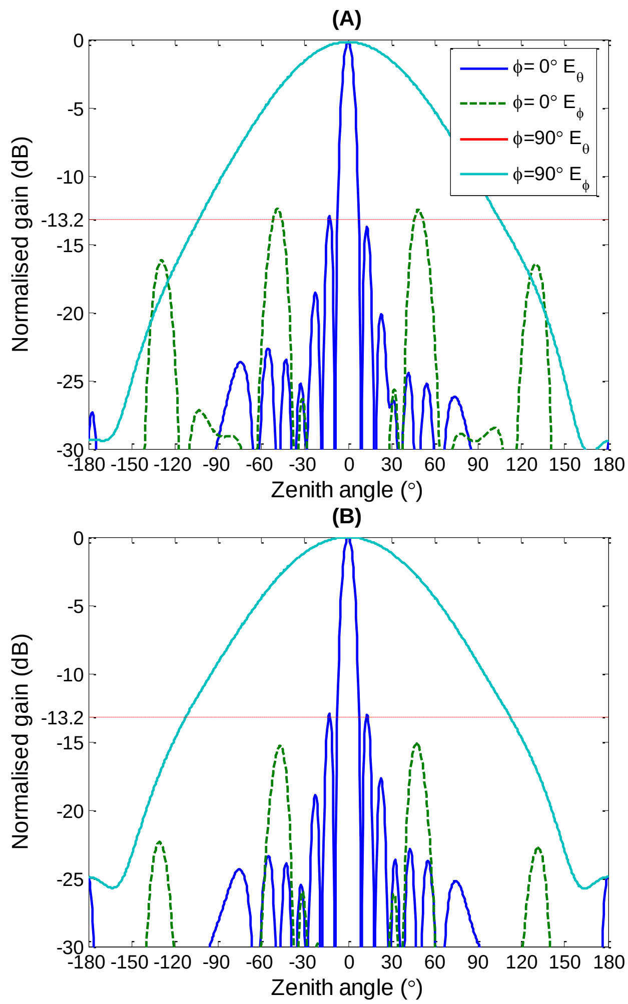

Figure 8. Radiation patterns of 1.27mm wall thickness 10 slot narrow-wall slotted WR-90 waveguide antennas at 10GHz, from FEKO™; (A) conventional slots, (B) Z-slots.