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Re-examination of Watson's microwave Yagi aerial

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Abstract A historical end-fire 34-slot travelling wave rectangular waveguide antenna has a more rigid structure than comparable travelling or leaky-wave end fire antennas. In simulation the published antenna design had peak directivity of 16.2dBi with 1dB directivity bandwidth of 12.2% but the matching was poor with $S_{11}\approx$-3dB. The feed section of the antenna was found to be independent of the travelling wave and front sections, enabling faster tuning. Changing the original narrow wall inclined slot feed to a narrow wall Z-slot gave $S_{11}\leq$-10dB bandwidth of 8% making the antenna of practical value. Comparison is made to a dielectric polyrod antenna which had comparable performance across an octave.

Key words polyrod antenna, travelling wave antenna.

1. Introduction

Between 1942 and 1944 fundamental work to develop shunt and series rectangular waveguide fed slot radiators at 2.8 and 9.375GHz was undertaken by W.H. Watson and E.W. Guptill at McGill University [1]. The majority of that work was on broadside or near broadside radiating standing wave and travelling wave waveguide antennas which are widely used today at X-band and higher showing the significant advance that that work was over prior work on coaxial cable fed dipole arrays for high power handling capability, low internal losses and structural strength. In contrast, the single end fire WR-90 antenna briefly described at the end of [1] has apparently been forgotten, not appearing in any subsequent open or restricted literature. If built from WR-90 or some other rectangular metal tube it would be more robust than the printed Yagi's developed for a 30GHz wireless office system [2-5] and dielectric antennas [6-8], and further could enclose a T/R module and thus protect it from physical abuse and ionizing radiation. Conversely, if built from metallized foam this antenna would be loss mass and have more degrees of freedom than a polyrod antenna. These potential advantages were motivation for building a copy and then undertaking a simulation study [9]. Those results are re-analyzed here, the modular nature of the antenna was investigated and an alternate feed section presented.

Figure 1: Photograph of a copy of Watson's Yagi antenna with 10-slot antenna for scale comparison.

2. Watson's microwave Yagi aerial

Here the S_{11} and directivity of a "free floating" polyrod antenna were taken as the baseline as it was a near ideal endfire antenna when fitted with an optimized cup reflector, Figure 2 [10, 11]. As Watson's Yagi did not have such an additional external reflector, it is fair to make comparison to the polyrod stripped of its. With a 45mm long feed section of cross-linked polystyrene filled

16mm diameter circular waveguide, the total length of the FEKO™ polyrod antenna model was 460mm, Figure 2. In contrast, the FEKO™ model of Watson's Yagi from Figure 58 of [1] was 382mm. It is acknowledged that been 2.5λ_0 shorter at 9.375GHz makes any direct comparison of these endfire antennas unfair but want to qualify the behavior of the antenna as originally published before undertaking any new design work.

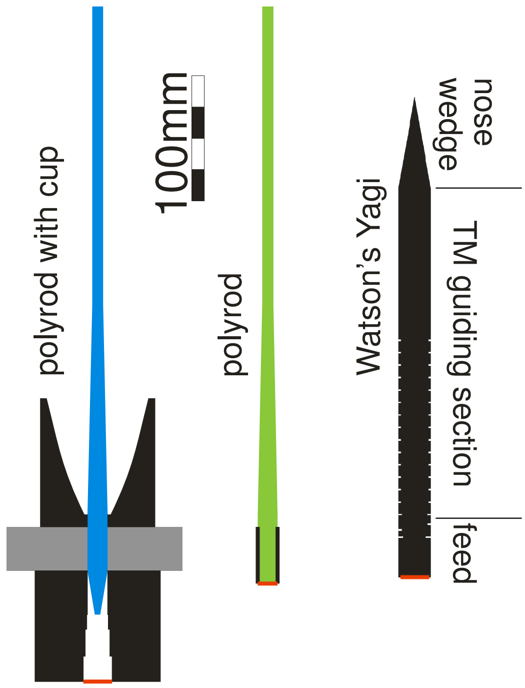

Figure 2: Watson's Yagi antenna compared to the optimized polyrod antenna from [11].

Full dimensioning for Watson's Yagi are given in Figure 58 of [1] and Figure 2 of [9]. The antenna consisted of 2 sets of 17 slots cut into the narrow walls of a section of WR-90 waveguide which terminated in a wedge and an internal shorting block just above the inclined radiating slots. All slots were 1.6mm wide. Sixteen of the 17 slots were transverse (not inclined) so did not couple to the dominant mode within the waveguide but did couple to the Transverse Magnetic (TM) surface wave on the outside of the waveguide. This makes the E-plane normal to the slotted narrow wall of the WR-90 rectangular waveguide, so the E-plane (ϕ=0°) of the antenna is in the plane of the page in Figure 2, making the H-plane (ϕ=90°) out of the page.

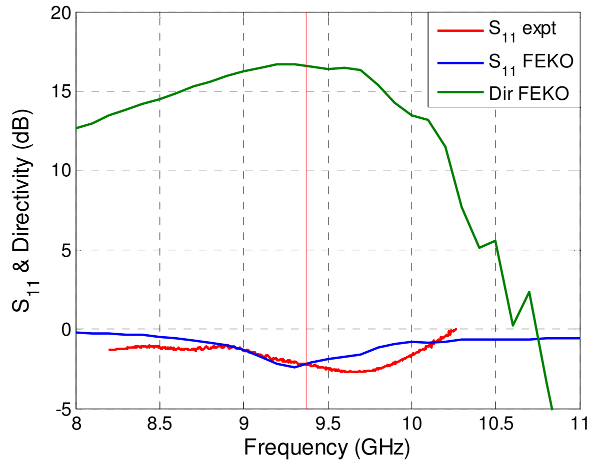

Figure 3: Simulated and measured performance of Watson's Yagi antenna.

Both the measured and simulated $S_{11}\leq$-3dB around 9.375GHz, Figure 3. This poor matching likely explains the non-publication beyond the diagram in Figure 58 of [1]. The resonance shift from 9.3GHz to 9.6GHz is speculated to be caused by a combination of minor manufacturing errors and interaction with the flange, which was not included in the FEKO™ model. In contrast, the peak directivity results were impressive for a relatively short antenna with 16.2dBi at 9.3GHz.

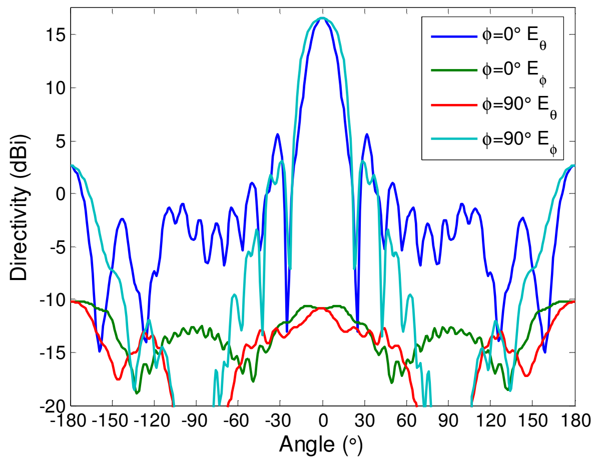

Figure 4: Simulated 9.375GHz radiation patterns of Watson's Yagi antenna, from FEKO™.

At 9.375GHz, Watson's Yagi produced a clean endfire radiation pattern, Figure 4. The E-plane 3dB beamwidth was narrower than that of the polyrod, while the H-plane was broader, Figure 4 and 5. Also in line with prior general analysis of endfire antennas [12], in opposition to the 3dB beamwidths, the E-plane first sidelobe levels were higher than those of the H-plane, Figures 4 and 6.

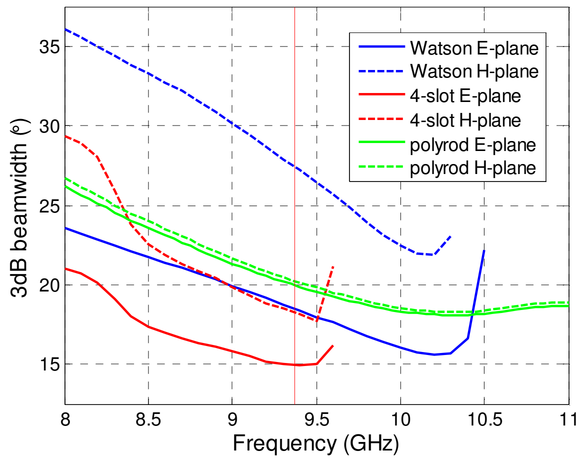

Figure 5: Simulated 3dB beamwidth of Watson's Yagi antenna, from FEKO™.

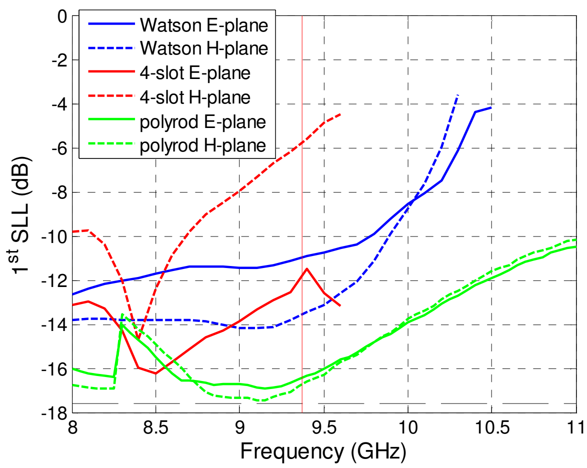

Figure 6: Simulated sidelobe level of Watson's Yagi antenna, from FEKO™.

3. Coupling tests of travelling wave slotted section

Having described the basic behavior of Watson's Yagi, the transverse slot travelling wave section was analyzed to see whether it constrained the directivity bandwidth of the antenna. A simple monopole coupling model along a short section of WR-90 waveguide was simulated in FEKO™, Figures 7 and 8. Adding 10 slots copied from Watson's Yagi between the monopoles increased the S_{21} from -22dB to -16dB at 9.375GHz, showing the ability of the slots to modify the near field of a monopole and to channel the TM wave along the narrow wall to be received by the second monopole.

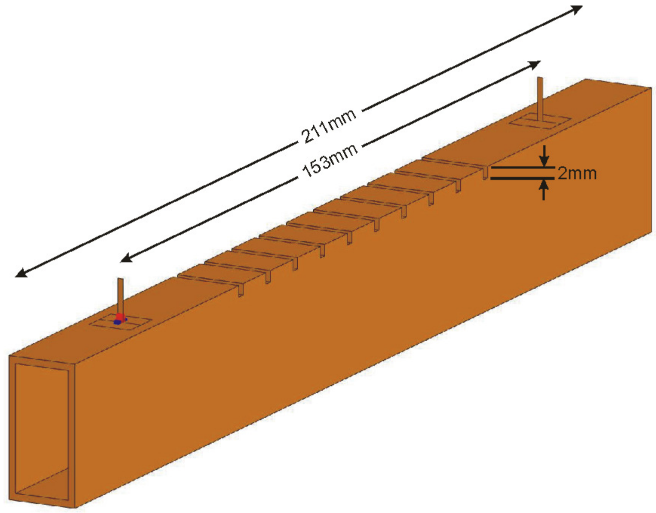

Figure 7: Annotated CAD of monopoles on WR-90 waveguide to test 10 transverse slots, from FEKO™.

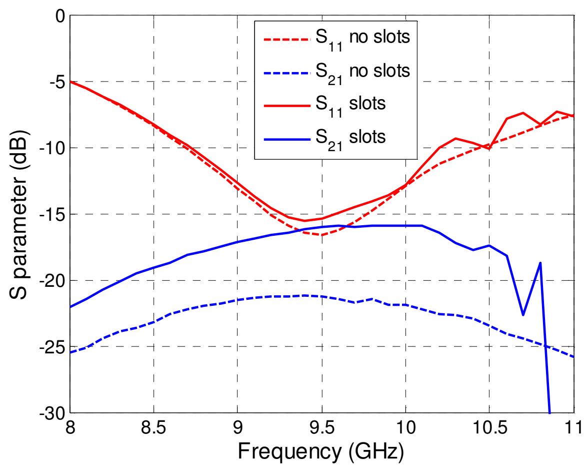

Figure 8: Simulated S-parameters of monopoles on WR90 waveguide section, from FEKO™.

Normalizing the peak directivity of Watson's Yagi and the S_{21} of the monopole coupling model enabled a direct comparison, Figure 9. There was not a straight mapping of the S_{21} to the antenna's peak directivity characteristic, suggesting that the transverse slot travelling wave section contributed to the behavior of the antenna along with some other factors possibly stemming from the poor S_{11} of the feed section.

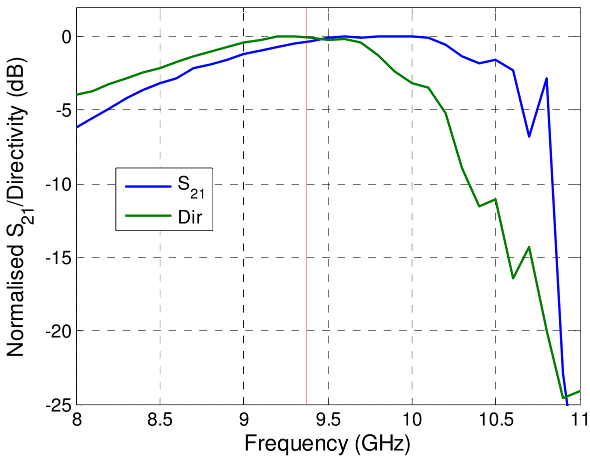

Figure 9: Comparison of monopole on WR-90 coupling and directivity of Watson's Yagi antenna, from FEKO™.

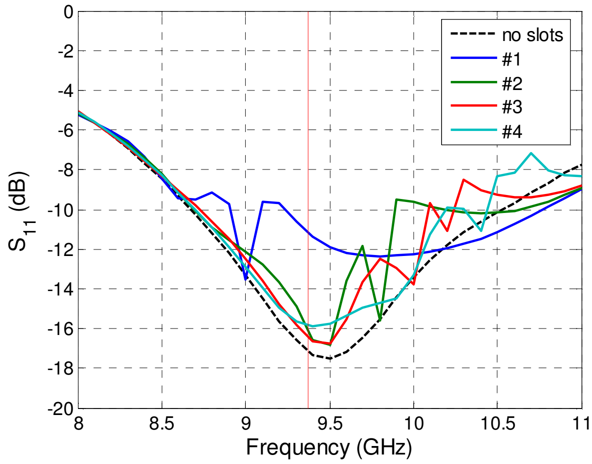

Figure 10: Simulated S_{11} of monopoles on 6063 aluminum tubing section, from FEKO™.

Changing to aluminum or carbon fiber reinforced plastic (CFRP) tube would decrease the mass of the antenna without compromising the structural strength. A readily available near WR-90 sized 6063 alloy aluminum tubing has internal dimensions of 22.6x9.6mm and 1.2mm wall thickness and cutoff frequency of 6.63GHz, as compared to 6.56GHz for WR-90. Four different combinations for slot cut depth and spacing were trialed to investigate the effect upon the passband, Table 1. The monopole coupling model of Figure 7 was resized to the 6063 tubing dimensions and rerun in FEKO™ for each pair of slot cut depth and slot spacing.

TABLE 1: Slot dimensions.

Name	Cut depth (mm)	Spacing (mm)
Watson's Yagi	2.0	9.92
#1	3.09	12.95
#2	2.73	11.27
#3	2.60	10.08
#4	2.35	9.65

All 4 slot arrangements introduced resonances to the transmitting monopole S_{11}, Figure 10. #1 caused the greatest disturbance as its pass-band stopped at 9GHz as seen in the S_{21}, Figure 11. #4 caused the least disturbance having its pass-band stop at 10.5GHz, thus been comparable to Watson's design. All slot arrangements increased the maximum S_{21} by 5dB as seen with the test of Watson's design.

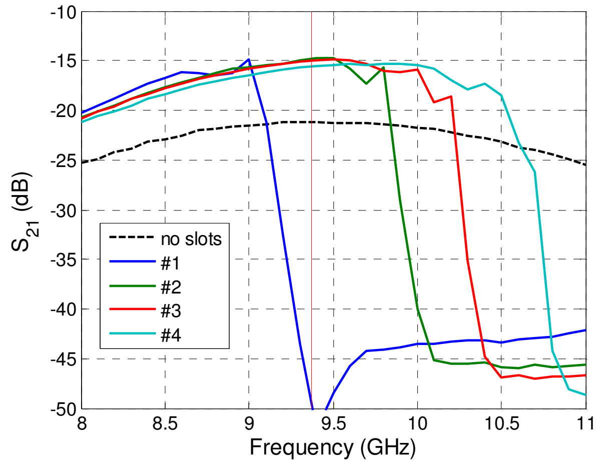

Figure 11: Simulated S_{21} of monopoles on 6063 aluminum tubing section, from FEKO™.

4. Aluminum antenna feeds

Having found that the transverse slot travelling section worked as well as possible, the feed section of Watson's Yagi was thus the sole cause of the poor matching. Having a single radiating slot in either narrow wall limited the bandwidth, and ideally the corners of the waveguide rectangular tube would not the cut so as to preserve structural strength. I or Z-slots fitting entirely within the narrow walls of rectangular waveguide have been used in arrays in the past [13, 14]. Initially different combinations of 3 Z-slots and U-slots were tried on a 382mm long antenna without the transverse slot travelling wave section to develop a well matched and directional feed at 9.375GHz. Later, different combinations of 4 slots were trialed. Both 3 and 4 slot narrow band matched feeds were developed and the better examples are given in Figure 12.

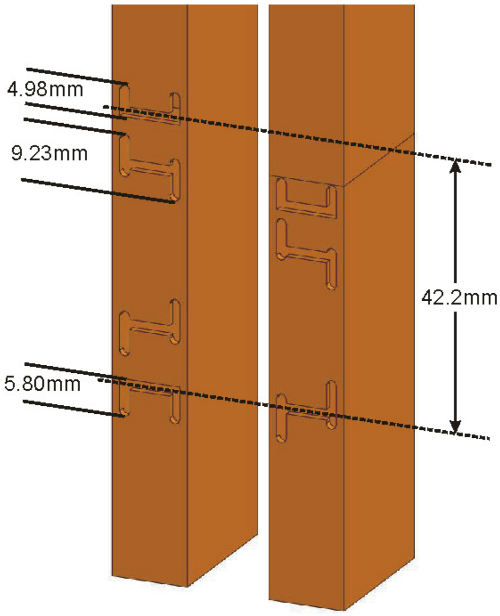

Figure 12: Annotated diagrams of 3 and 4 slot feeds.

All 4 transverse slot travelling wave arrangements from Table 1 were tried as a set of 14 slots started 8.8mm above the last feed slot. As with the monopole coupling model, #1 slot arrangement caused the greatest disturbance to the S_{11} of the 3 and 4 slot fed antennas, while #4 the least, Figures 13 and 14.

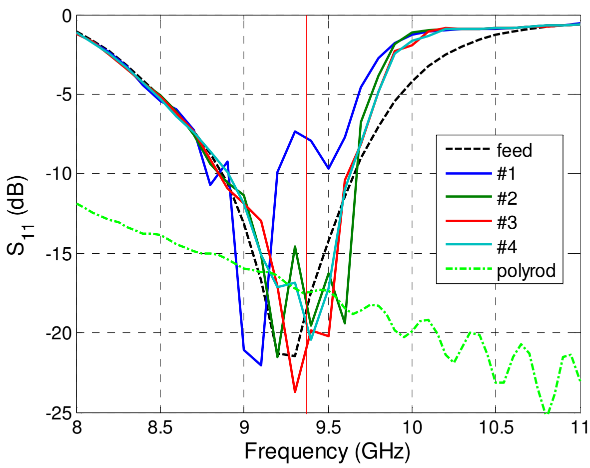

Figure 13: Simulated S_{11} of 3-slot feeds and 14 slot antennas and baseline polyrod; from FEKO™.

Slot arrangement #4 gave the widest directivity bandwidth for both 3 and 4-slot feeds, Figures 15 and 16. The highest directivity was 15.2dBi at 9.5GHz from the 4-slot fed antenna, Figure 16. This was 1dB lower than from Watson's Yagi. There was more radiation around θ=90° than in the E-plane pattern of Watson's Yagi accounting for the lower directivity, Figures 17 and 18.

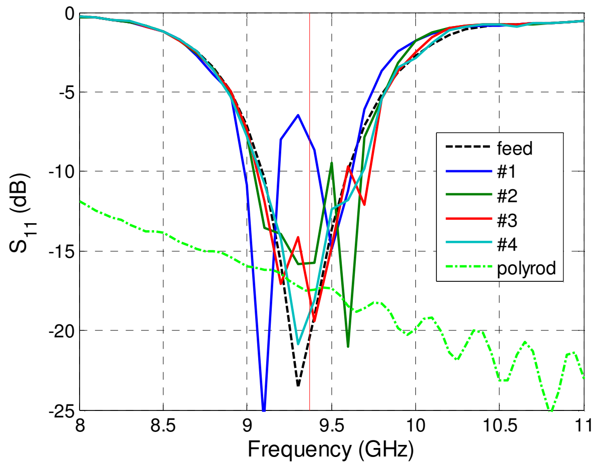

Figure 14: Simulated S_{11} of 4 slot feeds and 14 slot antennas and baseline polyrod; from FEKO™.

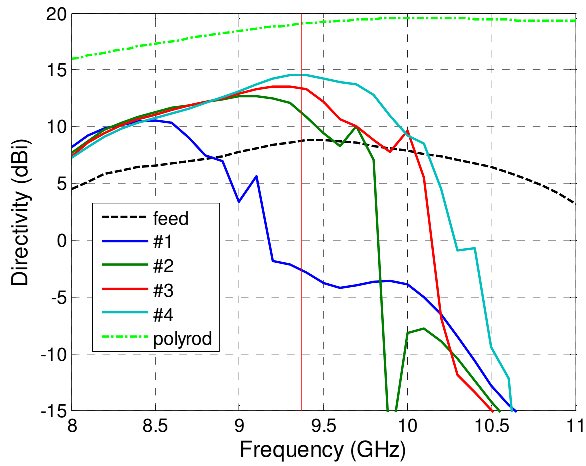

Figure 15: Simulated directivity of 3-slot feeds and 14 slot antennas and baseline polyrod; from FEKO™.

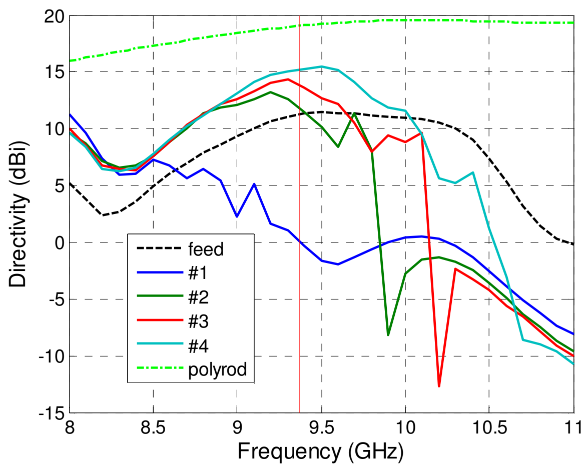

Figure 16: Simulated directivity of 4-slot feeds and 14 slot antennas and baseline polyrod; from FEKO™.

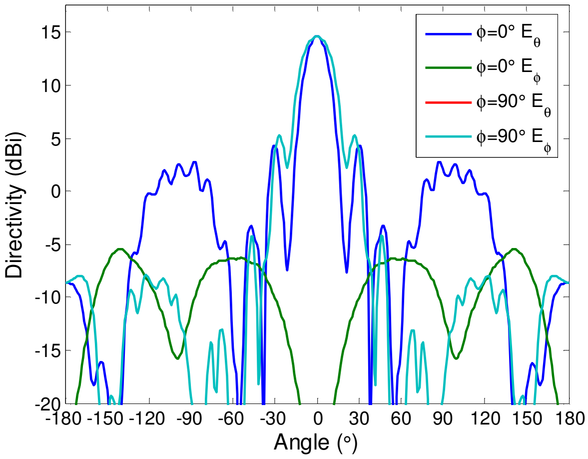

Figure 17: Simulated 9.375GHz radiation pattern of 3-slot antenna, from FEKO™.

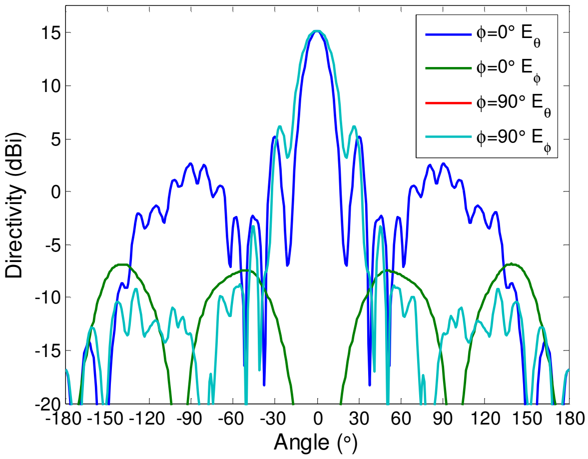

Figure 18: Simulated 9.375GHz radiation pattern of 4-slot antenna; from FEKO™.

5. Conclusions and future work

A historical "lost" endfire waveguide antenna was rebuilt and analyzed in FEKO™. The directivity performance was found to be quiet good for an antenna about $2\lambda_0$ shorter than optimal endfire length. However, the matching was poor explaining this antenna type's disappearance from the literature. The original travelling wave transverse slot design was found to be optimal, and a derivative worked well with 2 different new well matched feed sections. Future work will consider decreasing E-plane θ=90° radiation from the feeds, widening the bandwidth of those and increasing the antenna length.

Acknowledgement

Dr. P. Mousavi, his wife Dr. M. Deneshmand and their two children were murdered along with 172 other souls on January 8th, 2020 when Ukraine International Airlines Flight PS752 was shot down leaving Imam Khomeini International Airport. Our two friends and their children are greatly missed.

8. References

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