## Section 7-9.4 Multimode Smooth Wall High Aperture Efficiency Horns

## Bhattacharyya – Goyette Horn [1, 2]

This horn uses steps spaced so that the TM modes generated by one step is cancelled by the TM modes generated by the next step by phasing. It also generates higher order TE modes by using both steps and changes in slope within the horn bell. The first step generates the $TE_{12}$ mode while the second step generates the $TE_{13}$ mode. The diameter of the bell after these steps must be large enough to support these modes. With a $TE_{11}$ mode input the steps will generate $TE_{1j}$ and $TM_{1j}$ modes. The $TM_{1j}$ are undesirable because they generate cross polarization in the aperture. The change of slope along the horn bell generates $TE_{1j}$ modes that will propagate to the aperture if the diameter is large enough to support that circular waveguide mode. Changes of slope generate far less $TM_{1j}$ modes than steps.

Although the levels of each mode can be computed to produce a flat response across the aperture radius, practical design uses an optimization routine to vary the position and size of steps along with locations of slope changes to produce the best pattern. The examples below start with approximate designs given by the theory and use the min-max optimization of CHAMP (TICRA) to design the horns for a desired gain and bandwidth of low cross polarization.

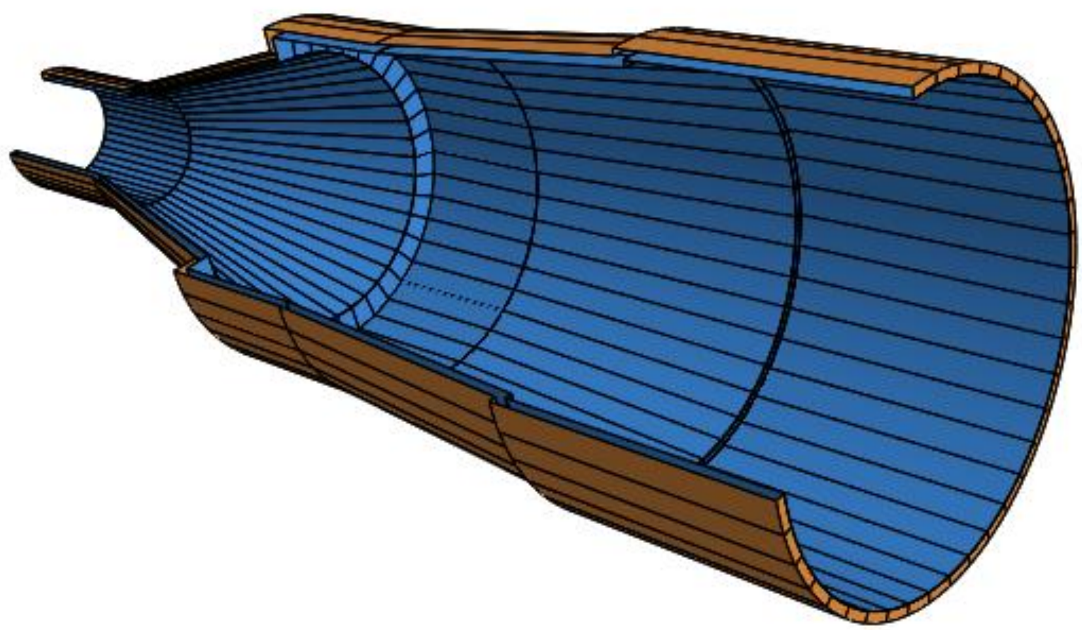

**Figure 7-9.4.1** Bhattacharyya – Goyette Horn designed for 16 dB gain 2.188λ aperture

The horn shown in Figure 7-9.4.1 starts from a feed waveguide 0.73λ in diameter with a linearly tapered section of length L1 to a diameter D1. At this point the bell has a finite step to a diameter D2 to generate the $TE_{12}$ mode. D2 must be large enough to support this mode (1.6971λ). Next there is a straight section of waveguide of length L2. A tapered section of waveguide L3 long tapers to the inner diameter (D3) of the next step. The diameter of the next step D4 must be able to support the $TE_{13}$ mode (2.7172λ). The lengths L2 and L3 have been designed so that the $TM_{11}$ mode generated by the first step is out-of-phase with the TM mode generated by the second step. Of course, the cancellation need only be approximately satisfied to reduce the aperture mode that generates cross polarization. The final length of the bell to the aperture diameter DA is given as the variable L4 which also phases the multiple modes that propagate at different phase velocities along the tapered section.

Table 7-9.4.1 summarizes a series of designs of the Bhattacharyya – Goyette horns with gain as the parameter. The aperture diameter, DA, is given in wavelengths at the center frequency. The column length (λ) is the sum of the lengths in the horn bell. An optimization was carried out to reduce radiated cross-polarization and maximize aperture efficiency. Aperture efficiency is given as percent and the cross polarization dB at the center frequency. These designs are only one possible solution where others are possible. Table 7-9.4.2 lists the dimensions in wavelengths at the center frequency.

**Table 7-9.4.1** Aperture and total bell length of optimized Bhattacharyya – Goyette horns

| Gain | Aperture | Length | Efficiency | X-pol | Lengths | Steps |
|---|---|---|---|---|---|---|
| 15.0 | 1.90950 | 4.7392 | 87.7 | -30.3 | 4 | 2 |
| 15.5 | 2.02409 | 4.9768 | 87.4 | -34.2 | 4 | 2 |
| 16.0 | 2.18818 | 5.5900 | 84.3 | -31.4 | 4 | 2 |
| 16.5 | 2.32716 | 5.9620 | 83.6 | -30.2 | 4 | 2 |
| 17.0 | 2.45061 | 6.0577 | 84.6 | -31.4 | 4 | 2 |
| 17.5 | 2.57174 | 6.1567 | 86.3 | -32.2 | 4 | 2 |
| 18.0 | 2.74606 | 6.5113 | 85.0 | -31.5 | 4 | 2 |
| 18.5 | 2.84595 | 6.5545 | 90.5 | -37.9 | 4 | 2 |
| 18.5 | 2.82649 | 6.5786 | 89.5 | -38.8 | 4 | 2 |
| 19.0 | 2.97895 | 6.8048 | 90.7 | -34.3 | 4 | 2 |
| 19.5 | 3.15057 | 7.0066 | 91.0 | -41.0 | 4 | 2 |
| 20.0 | 3.35261 | 7.4101 | 90.5 | -37.6 | 4 | 2 |
| 20.0b | 3.39690 | 7.2265 | 88.0 | -32.0 | 4 | 2 |
| 20.5 | 3.53380 | 7.6258 | 91.0 | -36.7 | 4 | 2 |
| 21.0 | 3.78720 | 8.0349 | 88.9 | -37.0 | 4 | 2 |
| 21.5 | 4.01751 | 8.3716 | 88.9 | -37.0 | 4 | 2 |
| 22.0 | 4.25957 | 8.7355 | 88.5 | -37.0 | 4 | 2 |
| 22.5 | 4.53072 | 9.1286 | 87.8 | -35.0 | 4 | 2 |
| 23.0 | 4.84340 | 9.5075 | 86.6 | -32.0 | 4 | 2 |
| 23.0 | 4.85026 | 9.5923 | 85.7 | -28.2 | 5 | 3 |
| 23.5 | 5.15233 | 10.078 | 86.6 | -30.2 | 5 | 3 |
| 24.0 | 5.48376 | 10.608 | 85.3 | -29.0 | 5 | 3 |
| 24.5 | 5.83707 | 11.159 | 83.4 | -29.3 | 5 | 3 |
| 25.0 | 6.22920 | 11.719 | 81.5 | -30.0 | 5 | 3 |

**Table 7-9.4.2** Center frequency lengths and diameters of bell dimensions (λ) of the optimized Bhattacharyya – Goyette horns

| Gain | L1 | L2 | L3 | L4 | L5 | D1 | D2 | D3 | D4 | D5 | D6 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 15.0 | 1.7109 | 0.7890 | 1.5926 | 0.6465 | | 1.6284 | 1.6778 | 1.6778 | 1.9095 | | |
| 15.5 | 1.7068 | 0.8313 | 1.6346 | 0.8041 | | 1.5580 | 1.8684 | 1.8684 | 2.0241 | | |
| 16.0 | 1.6932 | 0.8463 | 1.6495 | 1.4009 | | 1.5803 | 1.8876 | 2.1142 | 2.1882 | | |
| 16.5 | 1.7008 | 0.8835 | 1.6334 | 1.7442 | | 1.5751 | 1.9148 | 2.1077 | 2.3716 | | |
| 17.0 | 1.7230 | 0.8930 | 1.5303 | 1.9114 | | 1.5813 | 1.8873 | 2.2936 | 2.4506 | | |
| 17.5 | 1.7090 | 0.8564 | 1.5110 | 2.0804 | | 1.5844 | 1.8734 | 2.3277 | 2.5717 | | |
| 18.0 | 1.6632 | 0.8659 | 1.4631 | 2.5191 | | 1.5958 | 1.8969 | 2.4424 | 2.7460 | | |
| 18.5 | 1.6644 | 0.8741 | 1.4589 | 2.5812 | | 1.5884 | 1.8912 | 2.4803 | 2.8265 | | |
| 18.5 | 1.6637 | 0.8729 | 1.4591 | 2.5588 | | 1.5834 | 1.8916 | 2.4912 | 2.8460 | | |
| 19.0 | 1.6640 | 0.8732 | 1.4592 | 2.8083 | | 1.5850 | 1.8922 | 2.4804 | 2.8446 | | |
| 19.5 | 1.6653 | 0.8736 | 1.4600 | 3.0673 | | 1.5903 | 1.8899 | 2.4862 | 2.8462 | | |
| 20.0 | 1.6913 | 0.8705 | 1.4503 | 3.3980 | | 1.5870 | 1.8911 | 2.5024 | 2.8877 | | |
| 20.0b | 1.7019 | 1.3591 | 1.2959 | 2.8694 | | 1.7004 | 1.9308 | 2.4327 | 2.6591 | | |
| 20.5 | 1.6995 | 0.8375 | 1.4149 | 3.6739 | | 1.5697 | 1.9011 | 2.5257 | 2.8809 | | |
| 21.0 | 1.6861 | 0.8630 | 1.4436 | 4.0742 | | 1.5924 | 1.8920 | 2.5063 | 2.8732 | | |
| 21.5 | 1.6848 | 0.8608 | 1.4416 | 4.3843 | | 1.5937 | 1.9002 | 2.8704 | 2.8704 | | |
| 22.0 | 1.6849 | 0.8612 | 1.4429 | 4.7465 | | 1.5945 | 1.8975 | 2.5169 | 2.8707 | | |
| 22.5 | 1.6634 | 0.8623 | 1.4459 | 5.1570 | | 1.5929 | 1.9032 | 2.5298 | 2.8468 | | |
| 23.0 | 1.6192 | 0.8468 | 1.4483 | 5.5932 | | 1.6018 | 1.9041 | 2.5539 | 2.8508 | | |
| 23.0 | 1.6118 | 0.8361 | 1.4434 | 1.4274 | 4.2738 | 1.6499 | 1.9045 | 2.5072 | 2.8177 | 3.4035 | 3.6340 |
| 23.5 | 1.5898 | 0.8583 | 1.4577 | 1.4188 | 4.7529 | 1.6188 | 1.9111 | 2.5622 | 2.8134 | 3.4736 | 3.5847 |
| 24.0 | 1.5860 | 0.8695 | 1.4626 | 1.4228 | 5.2667 | 1.6173 | 1.9248 | 2.5748 | 2.8115 | 3.4886 | 3.5808 |
| 24.5 | 1.5827 | 0.8979 | 1.4747 | 1.4029 | 5.8011 | 1.6198 | 1.9380 | 2.5756 | 2.8020 | 3.5124 | 3.5827 |
| 25.0 | 1.5776 | 0.9190 | 1.4730 | 1.3712 | 6.3782 | 1.6280 | 1.9531 | 2.5593 | 2.7913 | 3.5265 | 3.5919 |

**Table 7-9.4.3** Waveguide modes in the radiating aperture of the optimized Bhattacharyya – Goyette horns in dB

| Gain | TE(1) | TE(2) | TE(3) | TE(4) | TE(5) | TE(6) | TM(1) | TM(2) | TM(3) | TM(4) | TM(5) | TM(6) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15.0 | -0.30 | -16.12 | | | | | -13.70 | | | | | |
| 15.5 | -0.31 | -19.49 | | | | | -12.55 | | | | | |
| 16.0 | -0.43 | -15.43 | | | | | -19.11 | | | | | |
| 16.5 | -0.57 | -13.99 | | | | | -12.42 | -13.68 | | | | |
| 17.0 | -0.66 | -13.02 | | | | | -15.18 | -11.88 | | | | |
| 17.5 | -0.60 | -12.08 | | | | | -17.98 | -13.14 | | | | |
| 18.0 | -0.71 | -10.88 | -29.37 | | | | -19.67 | -12.57 | | | | |
| 18.5 | -0.73 | -9.87 | -26.63 | | | | -20.39 | -14.10 | | | | |
| 18.5 | -0.73 | -9.59 | -26.58 | | | | -21.27 | -14.52 | | | | |
| 19.0 | -0.67 | -10.44 | -28.59 | | | | -24.42 | -13.38 | | | | |
| 19.5 | -0.65 | -10.70 | -25.68 | | | | -20.03 | -13.97 | | | | |
| 20.0 | -0.66 | -10.53 | -25.54 | | | | -22.50 | -13.69 | -31.85 | | | |
| 20.0b | -0.38 | -15.63 | -27.56 | | | | -16.92 | -15.01 | -33.05 | | | |
| 20.5 | -0.53 | -11.32 | -26.24 | | | | -18.80 | -17.44 | -30.61 | | | |
| 21.0 | -0.56 | -11.82 | -24.41 | -35.59 | | | -17.22 | -15.04 | -32.70 | | | |
| 21.5 | -0.57 | -12.16 | -23.96 | -33.56 | | | -16.92 | -14.54 | -35.18 | | | |
| 22.0 | -0.51 | -12.82 | -22.91 | -35.89 | | | -16.62 | -15.49 | -51.74 | -30.02 | | |
| 22.5 | -0.48 | -13.71 | -23.52 | -32.79 | | | -14.79 | -17.80 | -35.17 | -30.96 | | |
| 23.0 | -0.46 | -14.09 | -22.89 | -31.51 | -39.75 | | -13.64 | -21.14 | -30.68 | -37.12 | | |
| 23.0 | -0.70 | -11.54 | -29.30 | -28.84 | -42.10 | | -16.28 | -16.47 | -16.02 | -25.92 | | |
| 23.5 | -0.55 | -12.20 | -22.50 | -32.01 | -37.53 | | -14.27 | -20.30 | -26.62 | -41.07 | | |
| 24.0 | -0.54 | -12.64 | -20.90 | -31.61 | -38.16 | | -13.84 | -29.62 | -30.69 | -45.96 | -35.86 | |
| 24.5 | -0.56 | -12.85 | -19.55 | -30,62 | -37.92 | -42.69 | -13.53 | -20.63 | -35.27 | -50.00 | -33.62 | |
| 25.0 | -0.60 | -12.65 | -18.38 | -28.94 | -35.76 | -40.64 | -13.73 | -19.73 | -29.76 | -44.34 | -33.91 | |

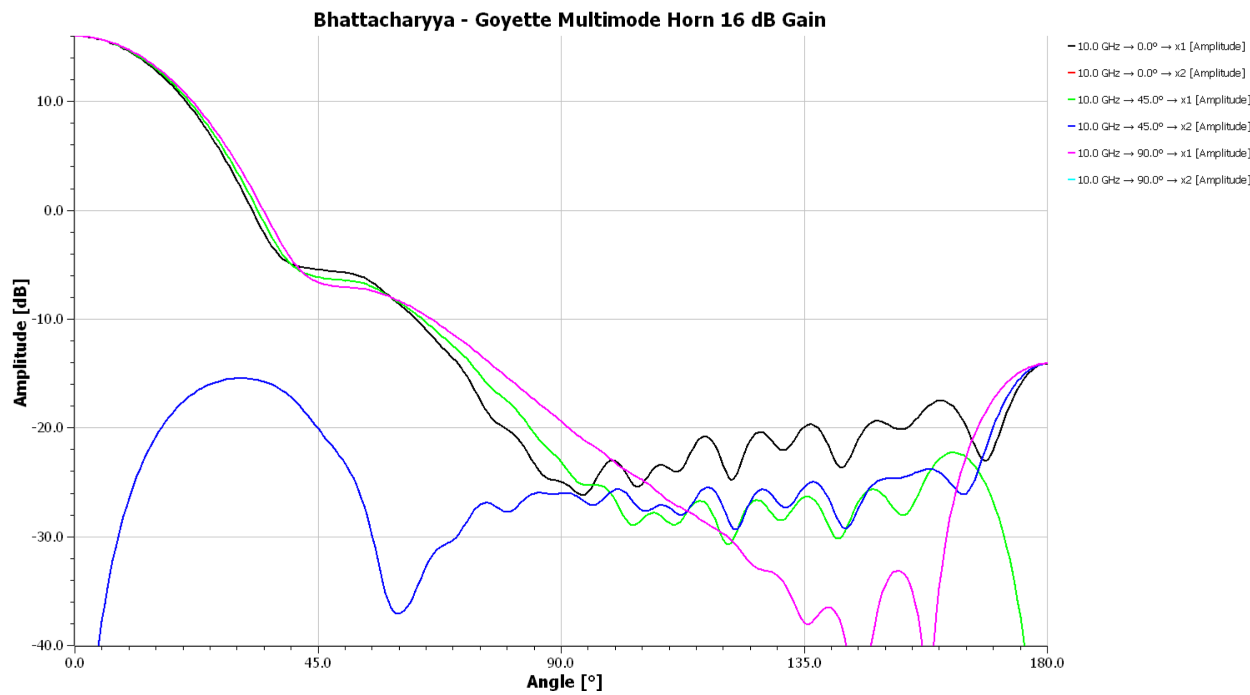


**Figure 7-9.4.2** Center frequency pattern of Bhattacharyya – Goyette Horn designed for 16 dB gain

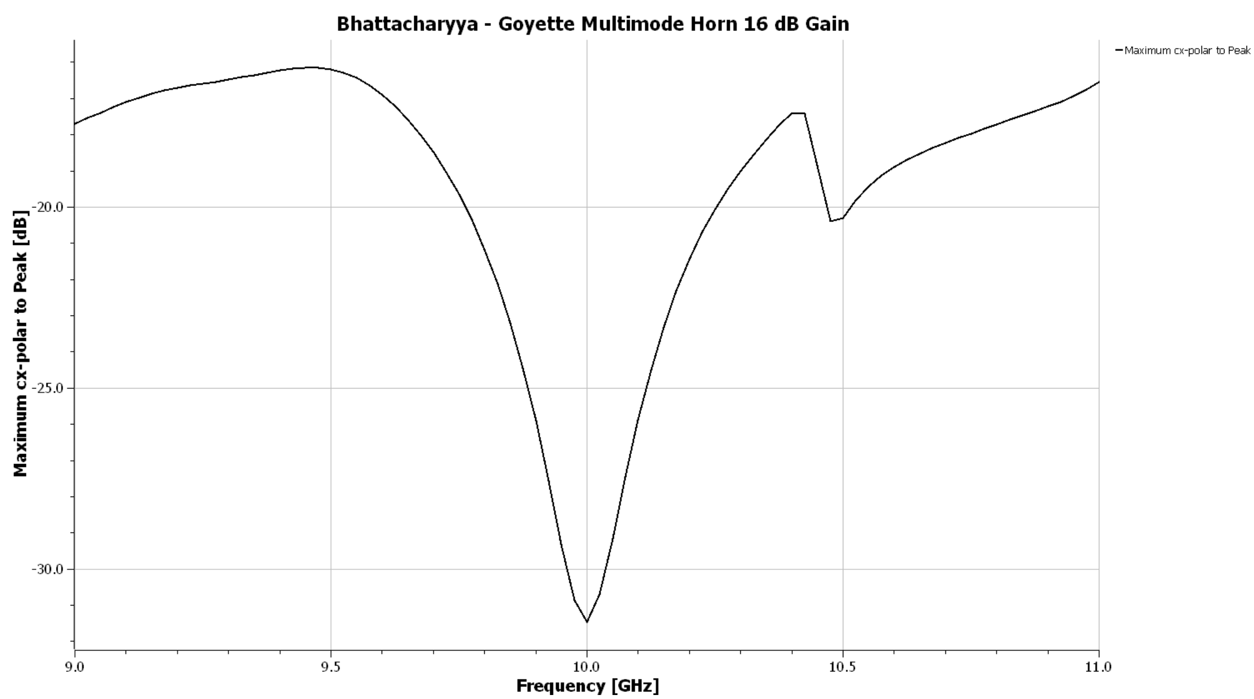


**Figure 7-9.4.3** Cross polarization response of Bhattacharyya – Goyette Horn designed for 16 dB gain

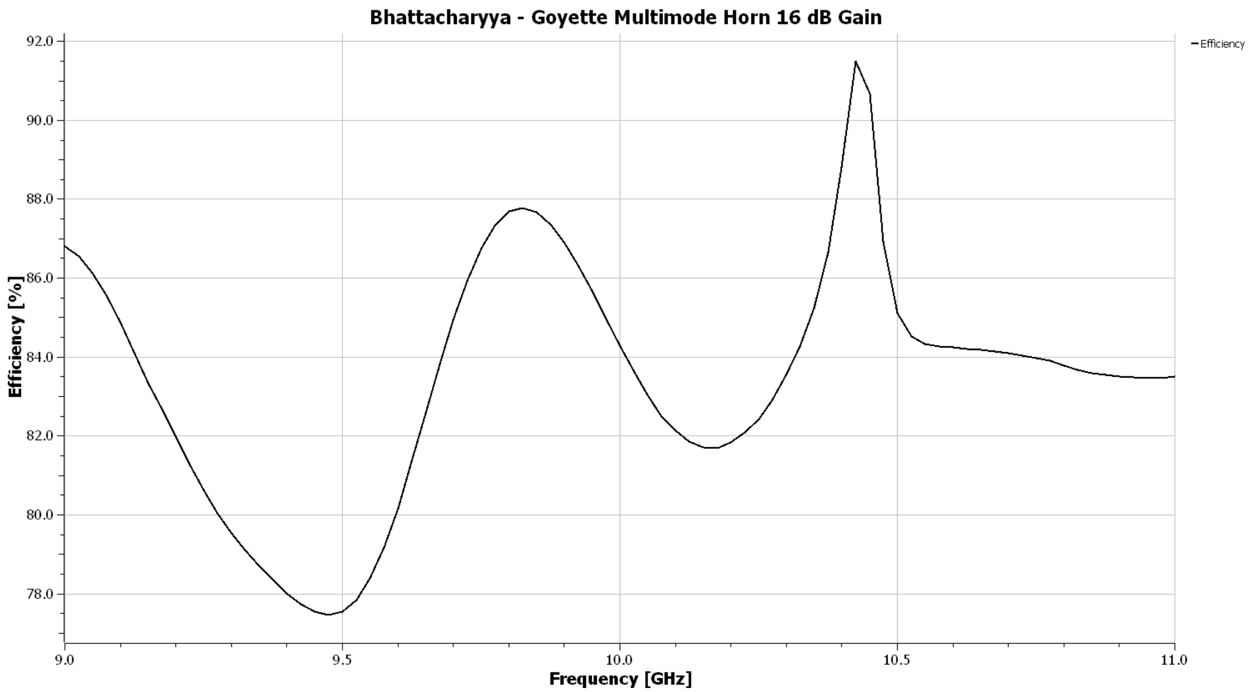


**Figure 7-9.4.4** Aperture efficiency of Bhattacharyya – Goyette Horn designed for 16 dB gain

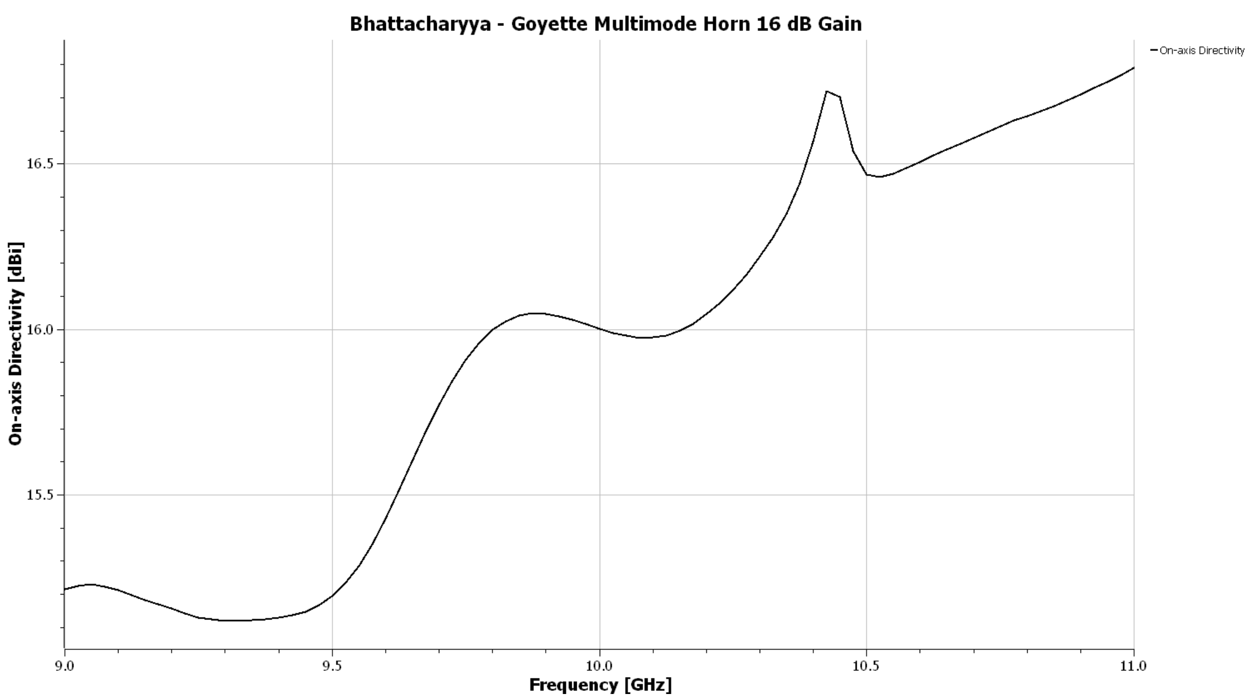


**Figure 7-9.4.5** On-axis Directivity of Bhattacharyya – Goyette Horn designed for 16 dB gain

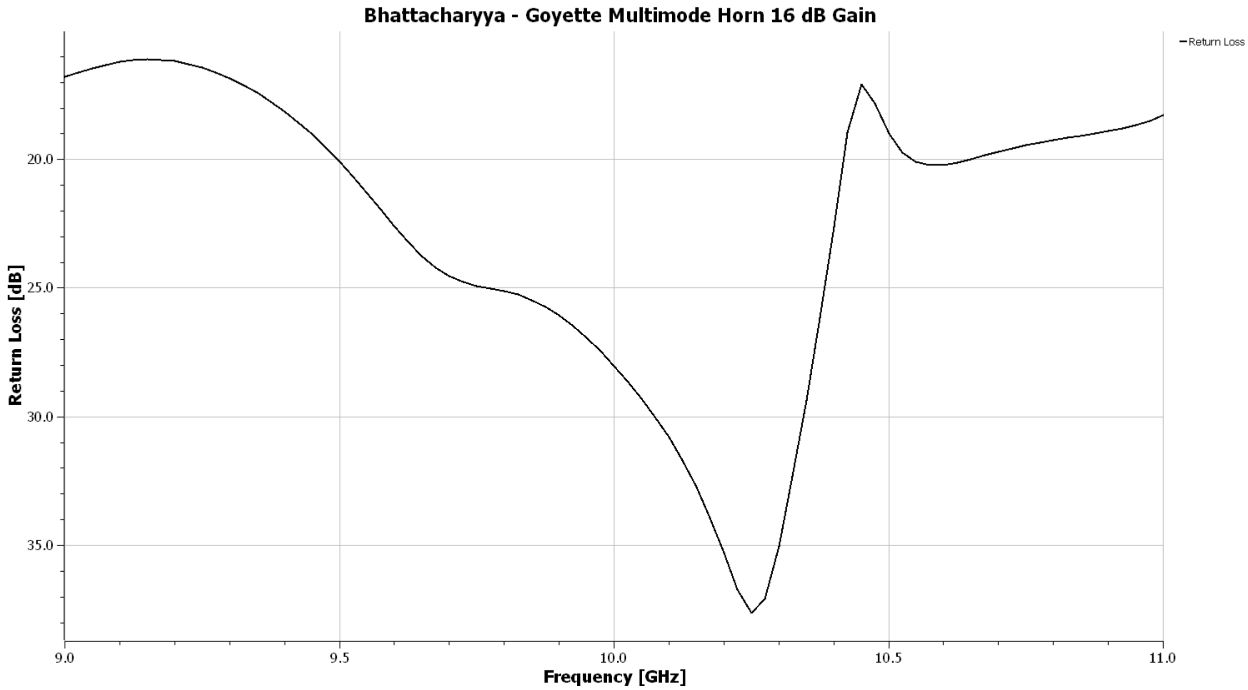


**Figure 7-9.4.6** Return Loss of Bhattacharyya – Goyette Horn designed for 16 dB gain

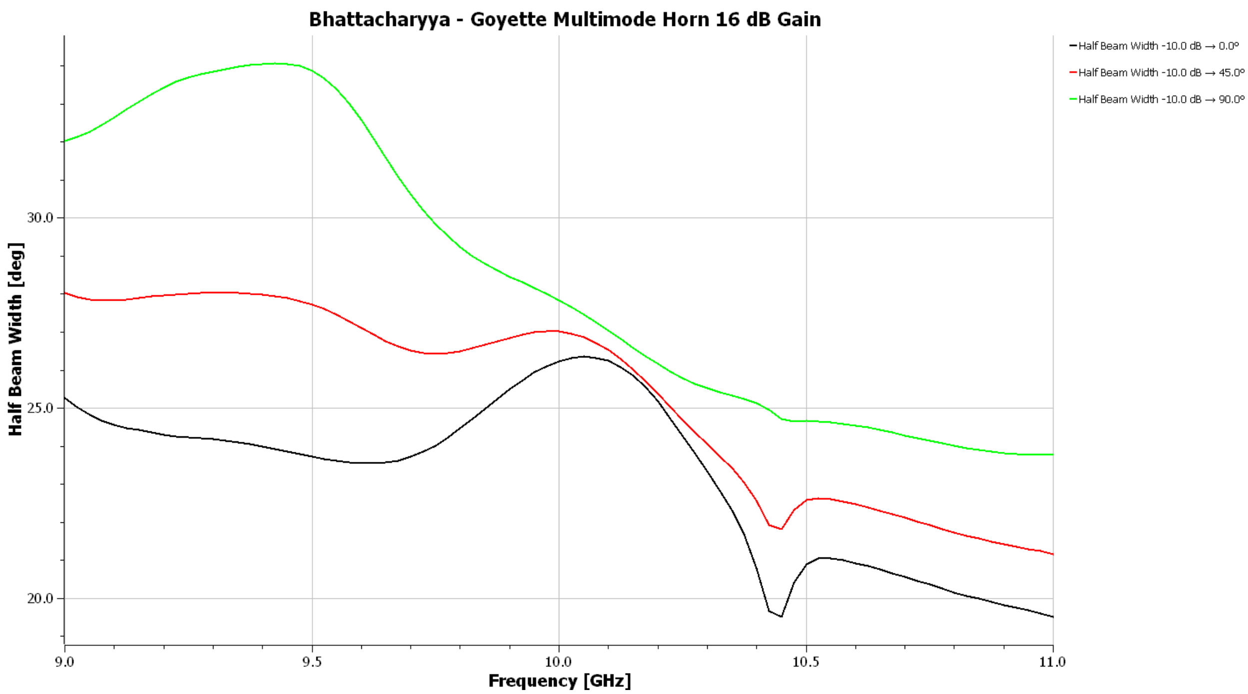


**Figure 7-9.4.7** 10 dB Half Beamwidth of Bhattacharyya – Goyette Horn designed for 16 dB gain

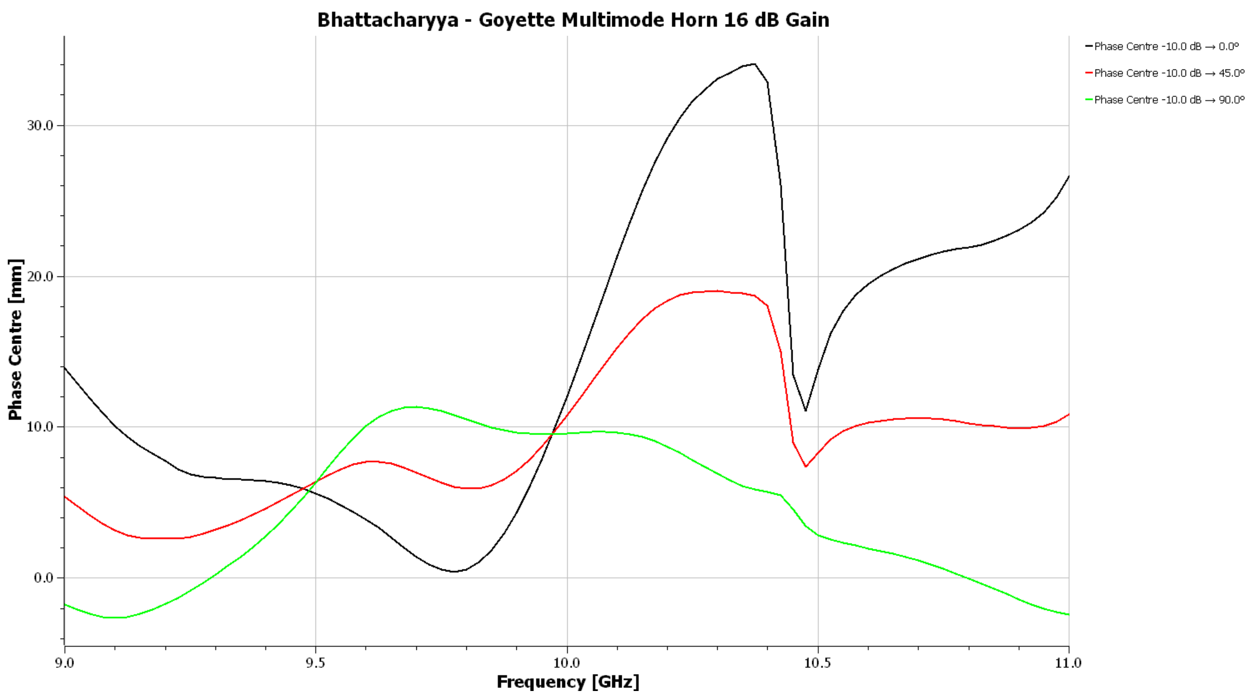


**Figure 7-9.4.8** 10 dB Phase Center of Bhattacharyya – Goyette Horn designed for 16 dB gain

## 20 dB Gain Bhattacharyya – Goyette Horn 3.353λ Aperture

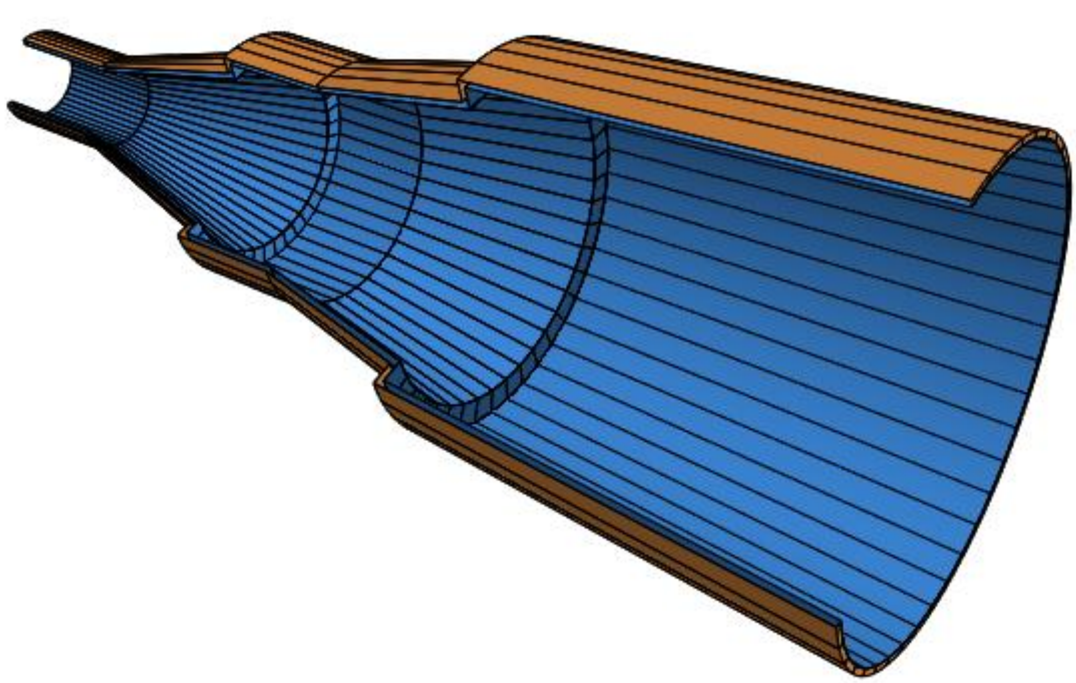

**Figure 7-9.4.9** Bhattacharyya – Goyette Horn designed for 20 dB gain

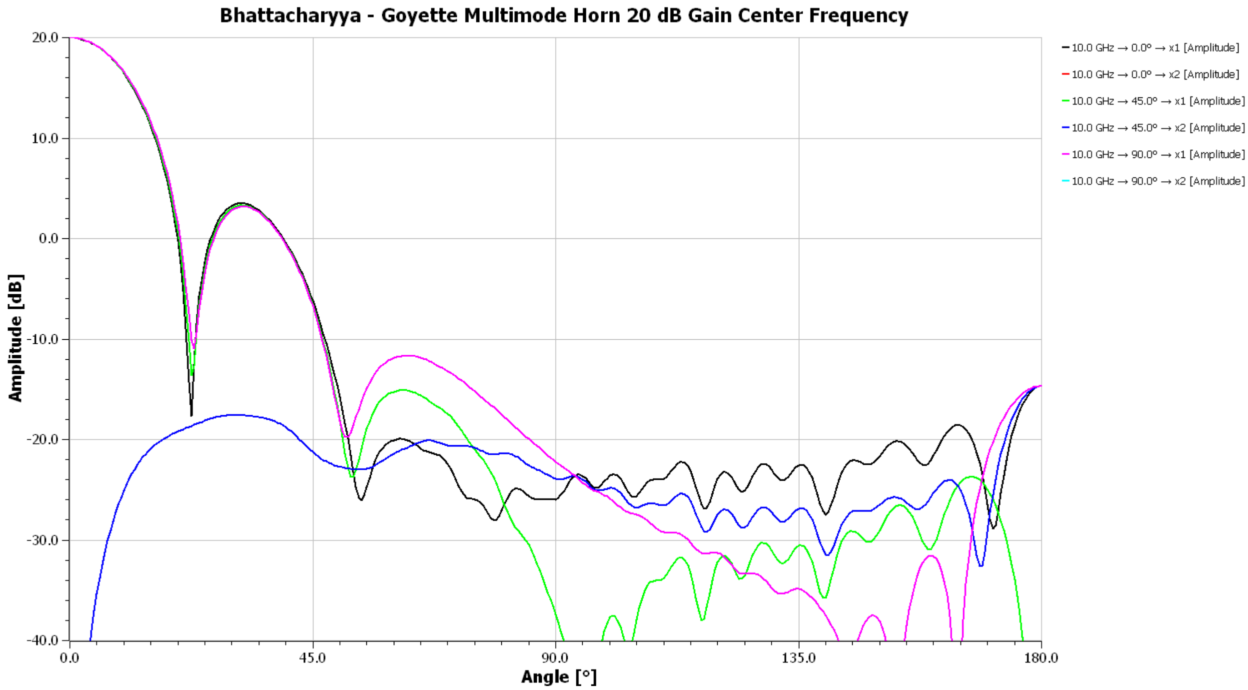


**Figure 7-9.4.10** Center frequency pattern of Bhattacharyya – Goyette Horn designed for 20 dB gain 1% Opt. Band

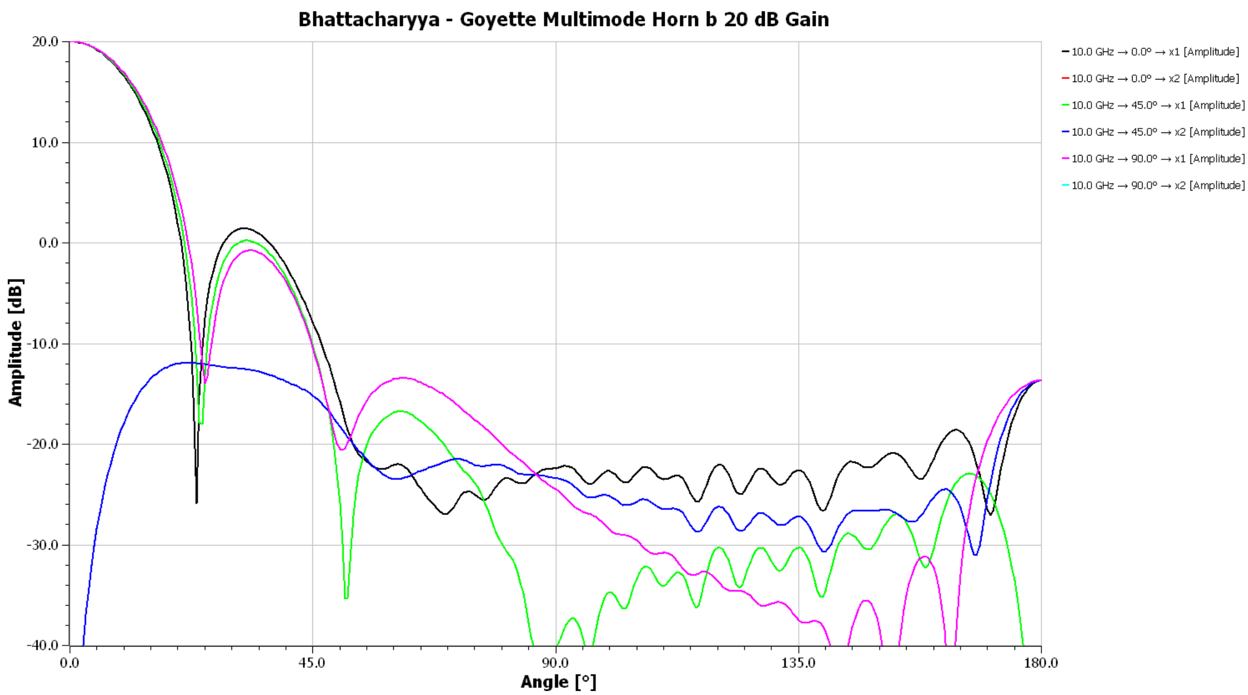


**Figure 7-9.4.11** Center frequency pattern of Bhattacharyya – Goyette Horn b designed for 20 dB gain 4% Opt. Band

Horn b was optimized over a 4% bandwidth while the original design was optimized over a 1% bandwidth

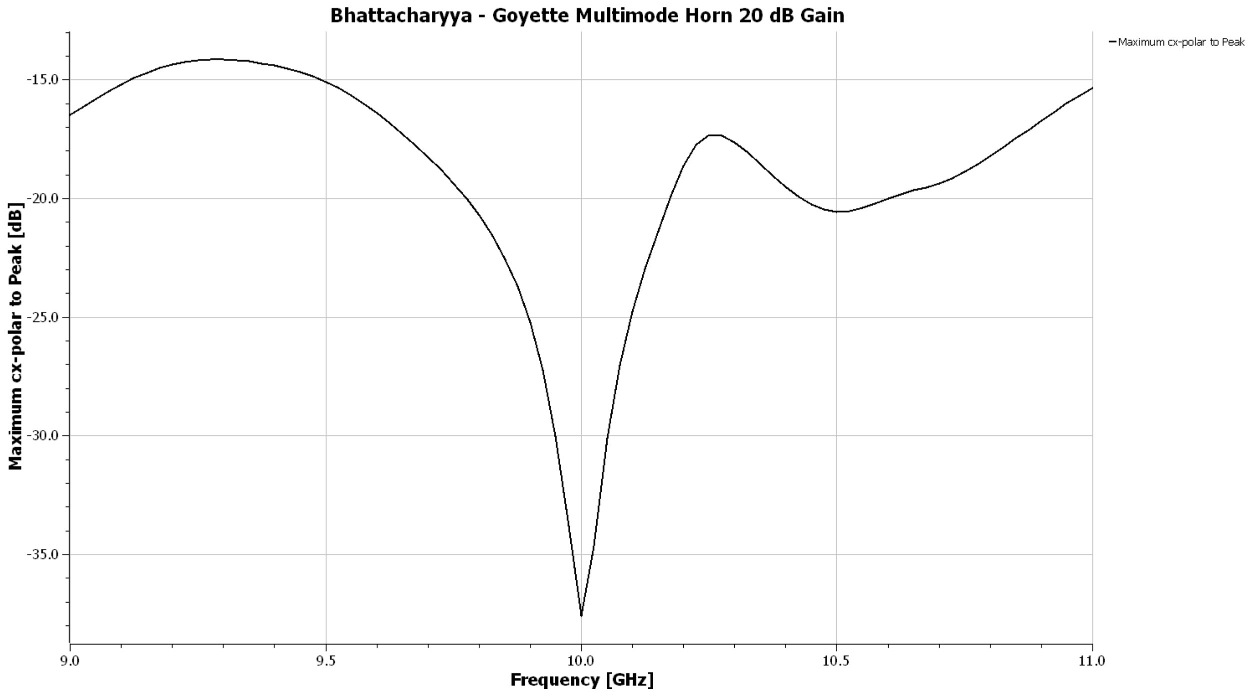


**Figure 7-9.4.12** Cross polarization response of Bhattacharyya – Goyette Horn designed for 20 dB gain 1% Opt. Band

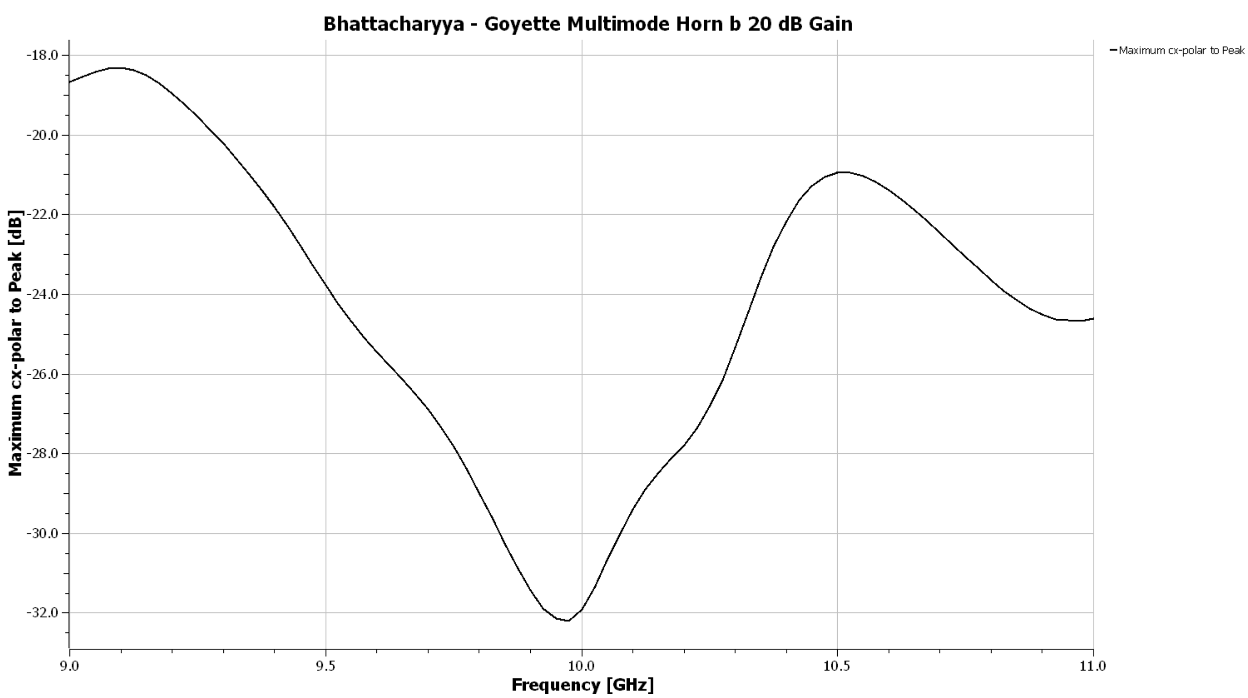


**Figure 7-9.4.13** Cross polarization response of Bhattacharyya – Goyette Horn b designed for 20 dB gain 4% Opt. Band

Horn b has a 7.2% bandwidth at -25 dB cross polarization while the original design has a 2% bandwidth.

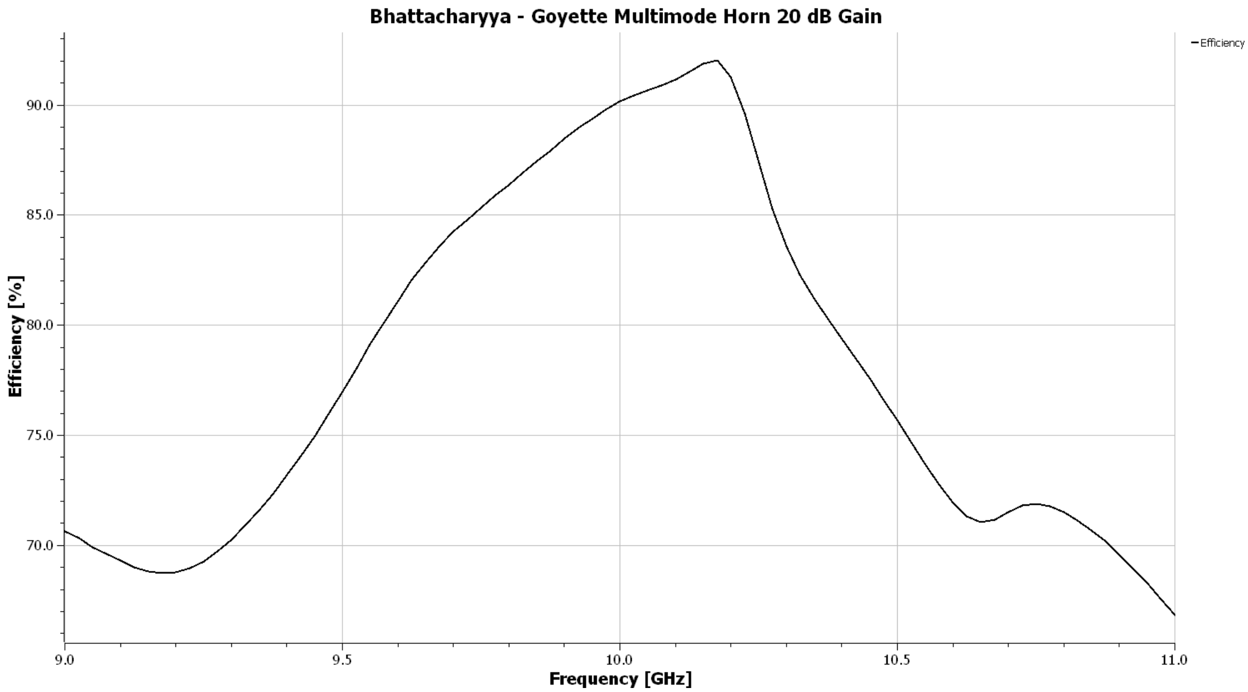


**Figure 7-9.4.14** Aperture efficiency of Bhattacharyya – Goyette Horn designed for 20 dB gain 1% Opt. Band

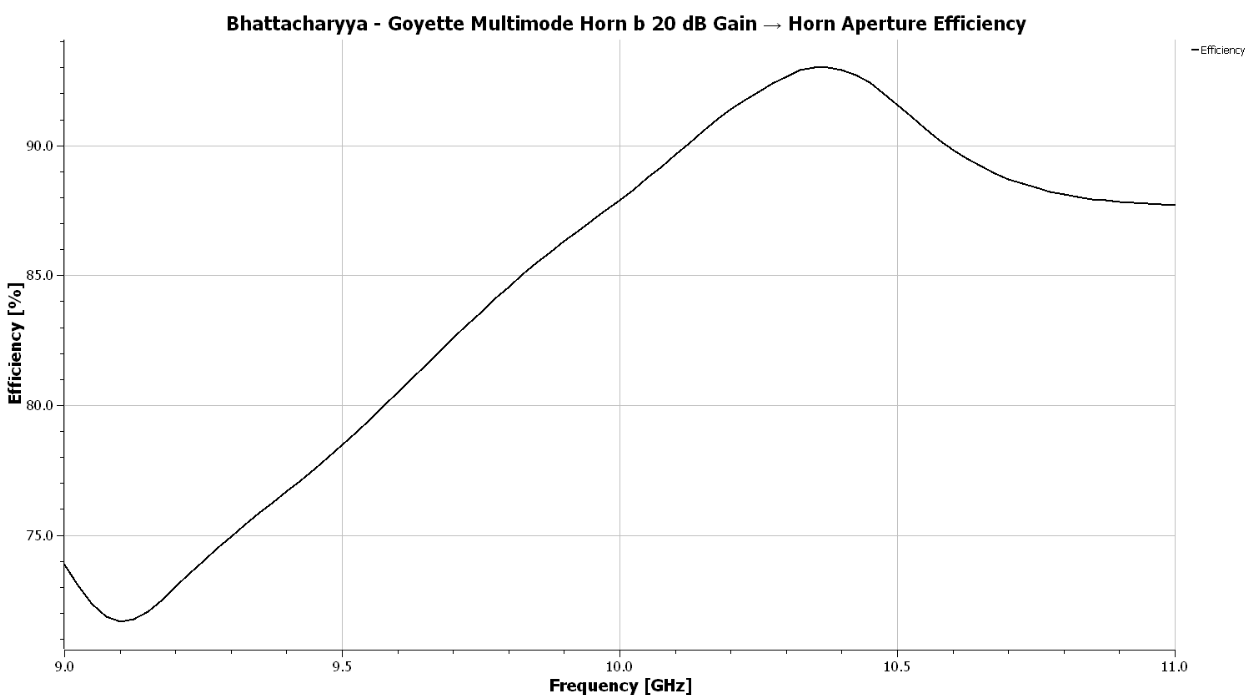


**Figure 7-9.4.15** Aperture efficiency of Bhattacharyya – Goyette Horn b designed for 20 dB gain 4% Opt. Band

The center frequency aperture efficiency drops from 90% to 88% with the aperture 3.3526λ increases to 3.3969λ to achieve 20 dB gain.

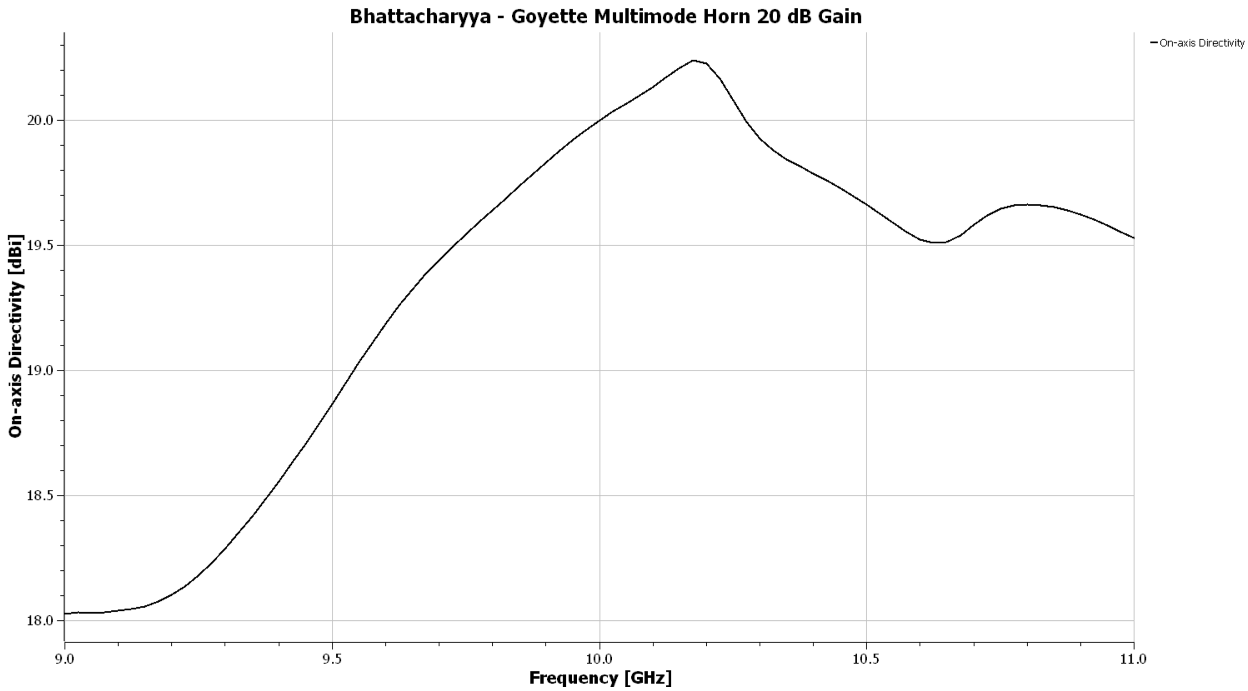


**Figure 7-9.4.16** On-axis Directivity of Bhattacharyya – Goyette Horn designed for 20 dB gain 1% Opt. Band

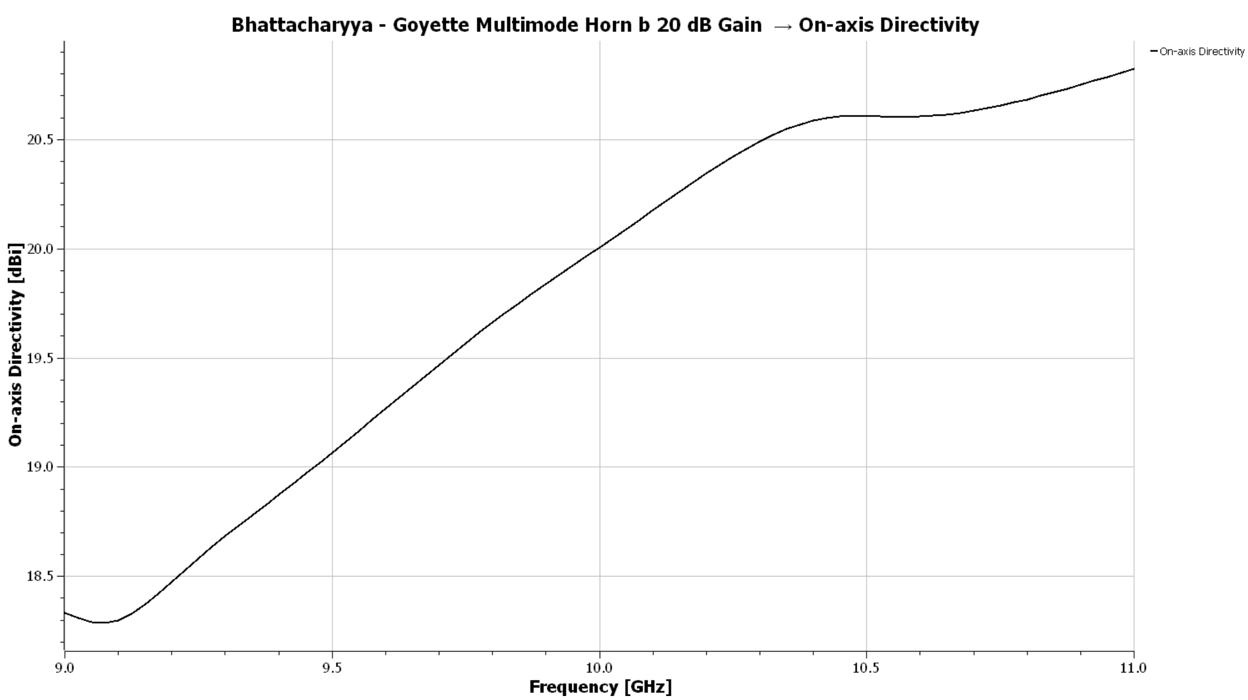

**Figure 7-9.4.17** On-axis Directivity of Bhattacharyya – Goyette Horn b designed for 20 dB gain 4% Opt. Band

The gain slope at center frequency decreases for the wider band optimization (Horn b).

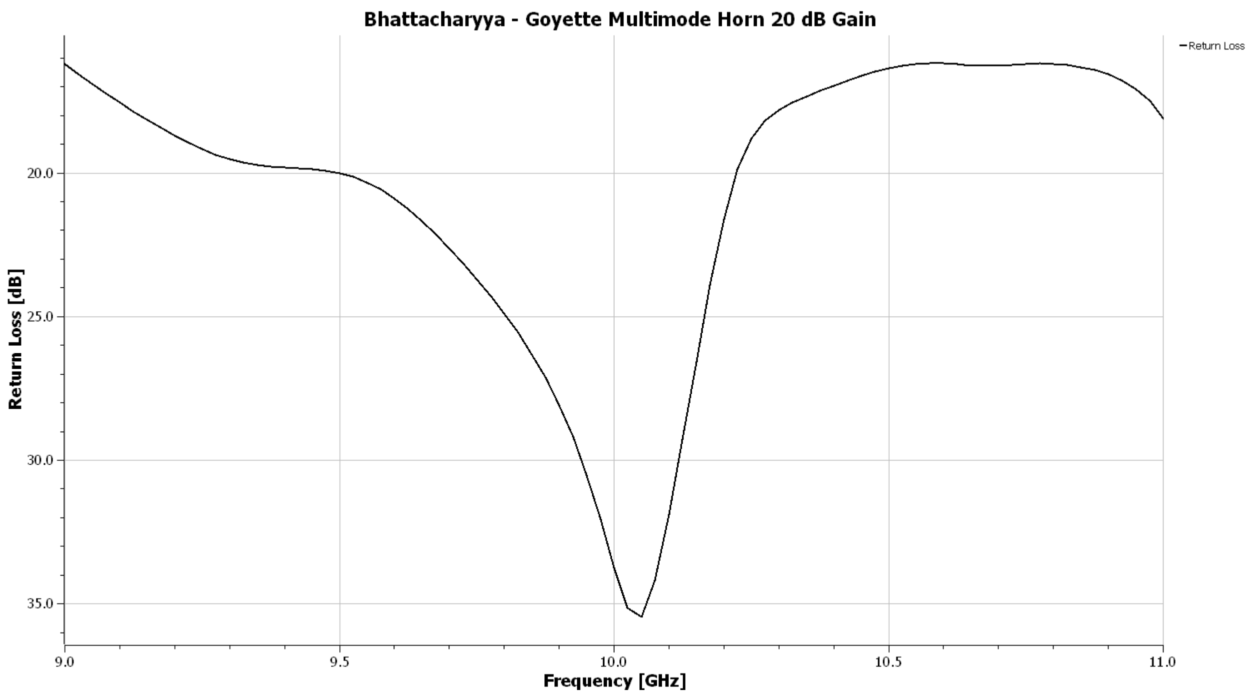


**Figure 7-9.4.18** Return Loss of Bhattacharyya – Goyette Horn designed for 20 dB gain 1% Opt. Band

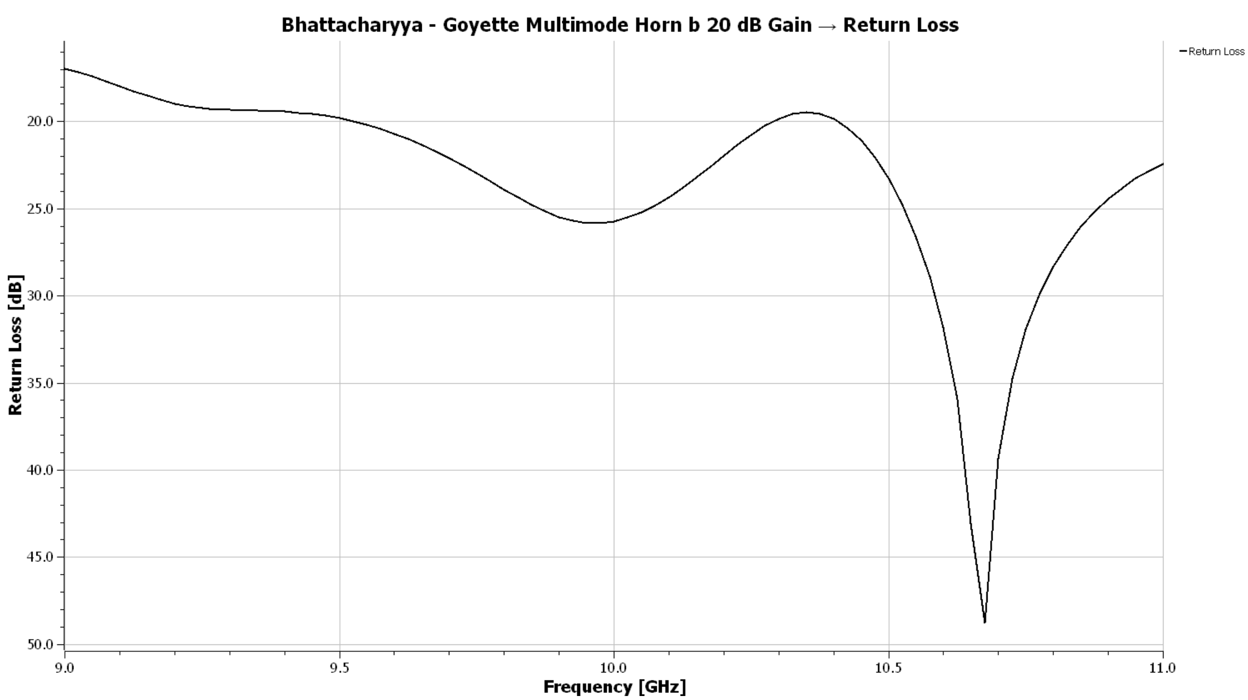

**Figure 7-9.4.19** Return Loss of Bhattacharyya – Goyette Horn b designed for 20 dB gain 4% Opt. Band

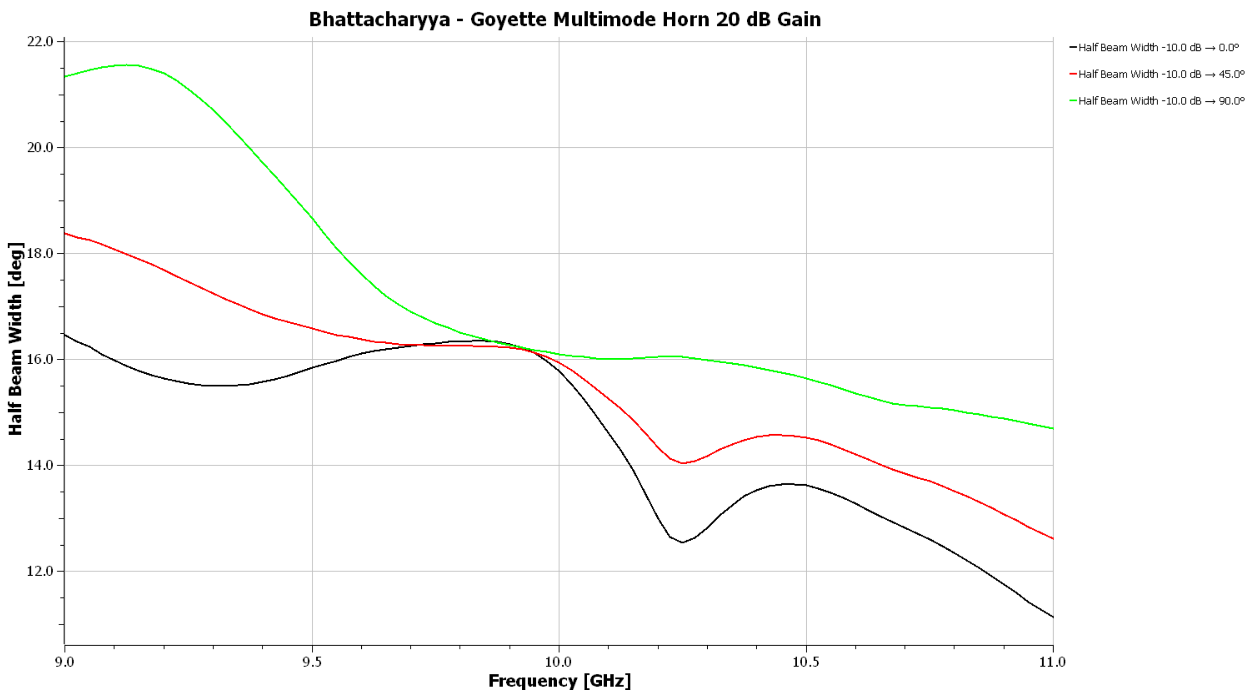


**Figure 7-9.4.20** 10 dB Half Beamwidth of Bhattacharyya – Goyette Horn designed for 20 dB gain 1% Opt. Band

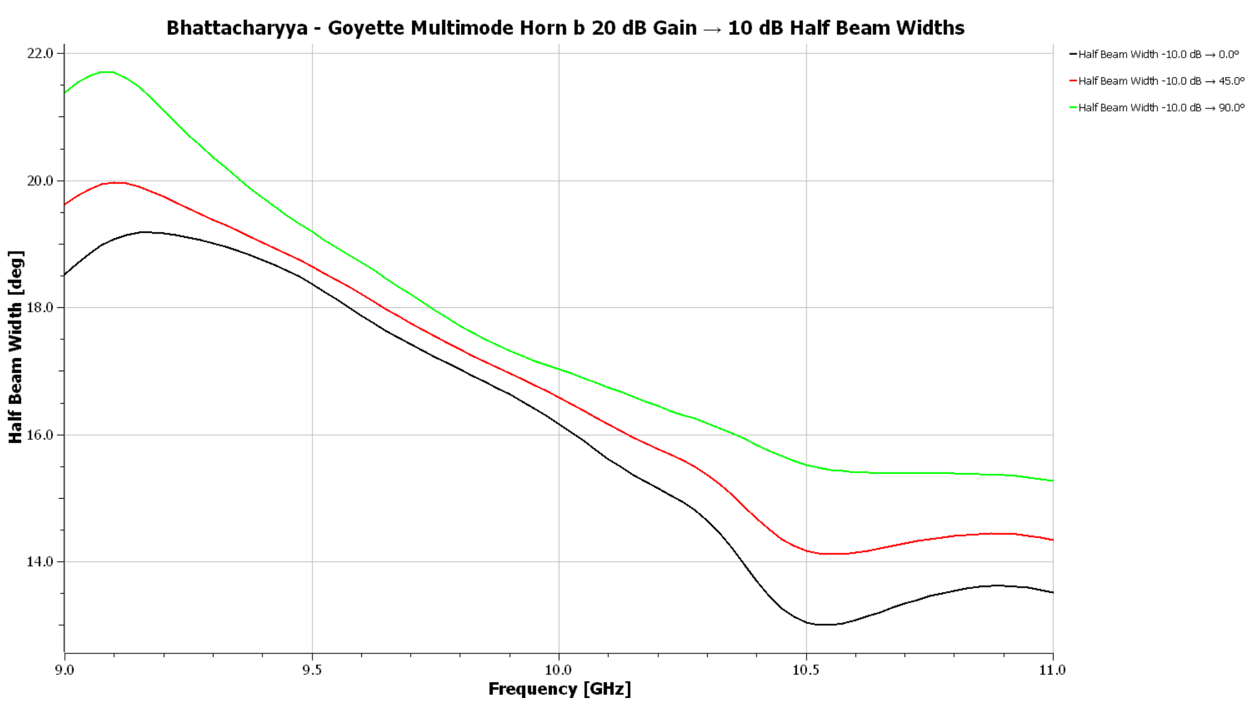

**Figure 7-9.4.21** 10 dB Half Beamwidth of Bhattacharyya – Goyette Horn b designed for 20 dB gain 4% Opt. Band

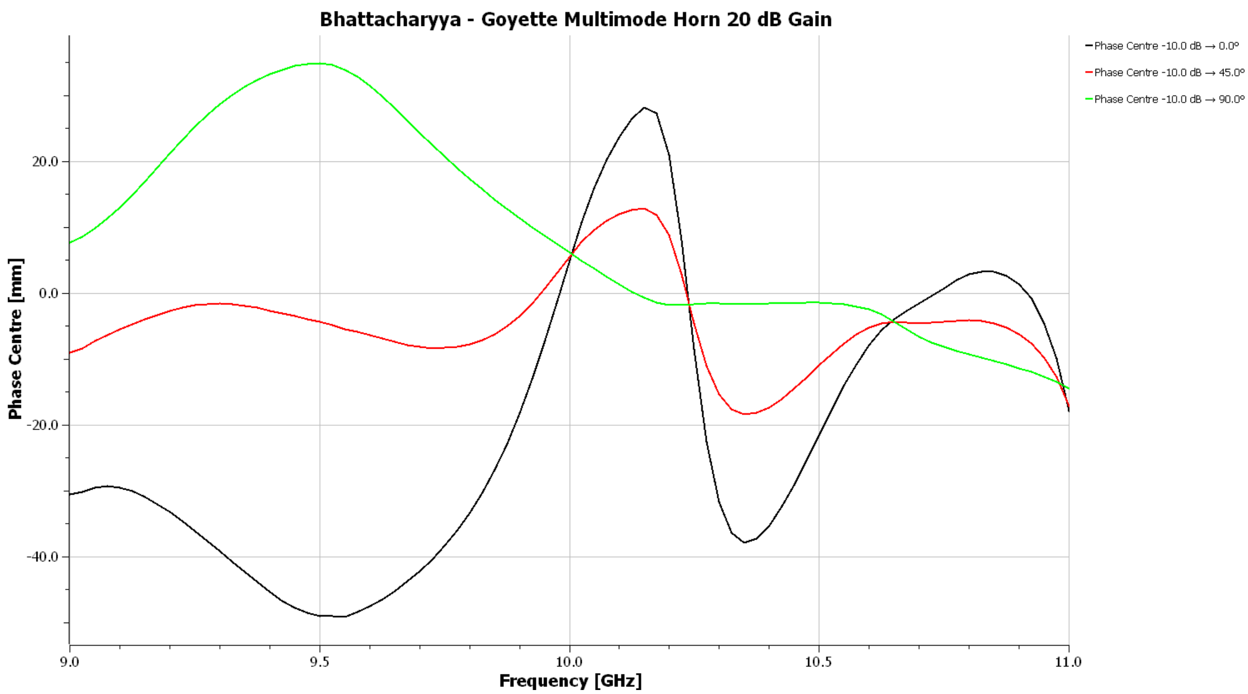


**Figure 7-9.4.22** 10 dB Phase Center of Bhattacharyya – Goyette Horn designed for 20 dB gain1% Opt. Band

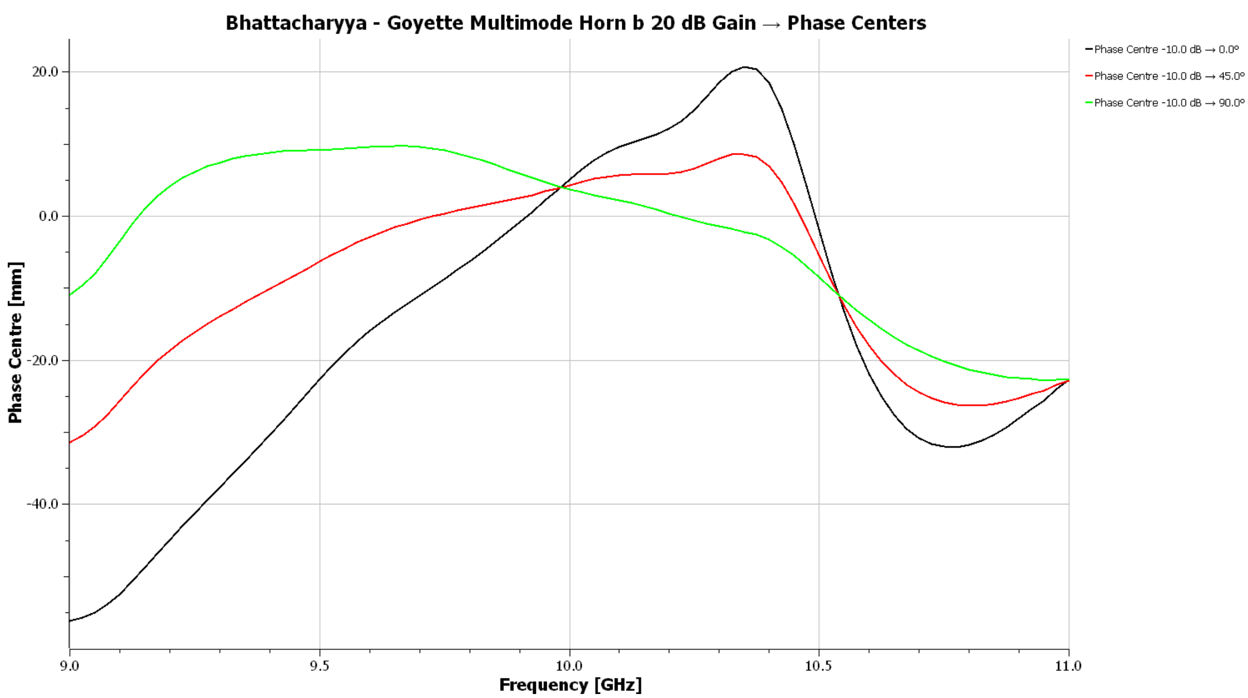

**Figure 7-9.4.23** 10 dB Phase Center of Bhattacharyya – Goyette Horn b designed for 20 dB gain 4% Opt. Band

## 24 dB Gain Bhattacharyya – Goyette Horn (3 steps) 5.484λ Aperture

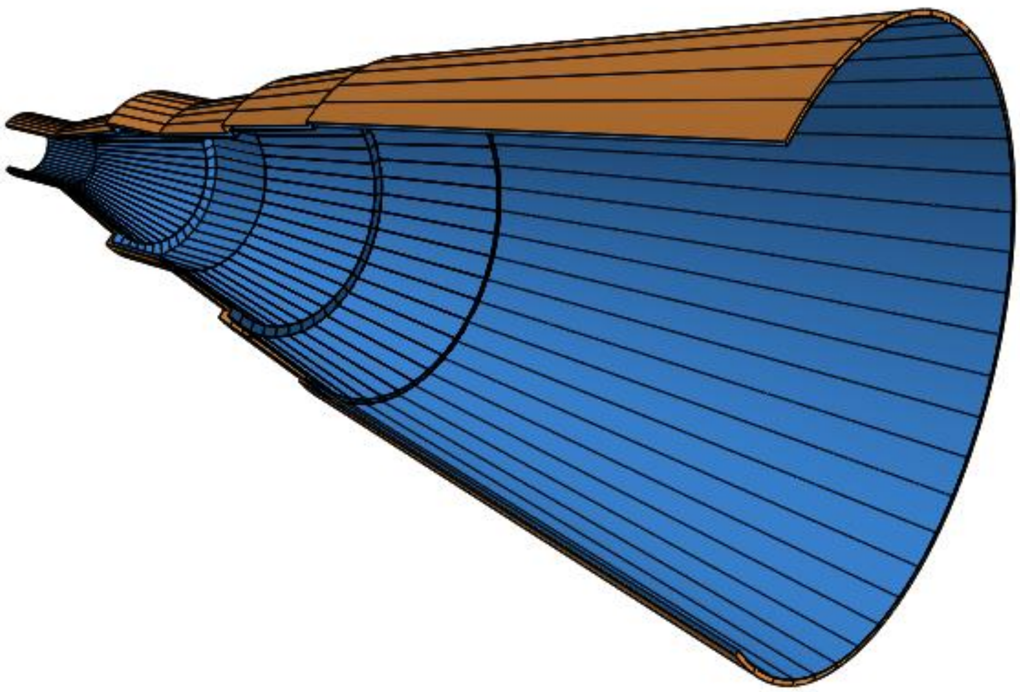

**Figure 7-9.4.24** Bhattacharyya – Goyette Horn designed for 24 dB gain

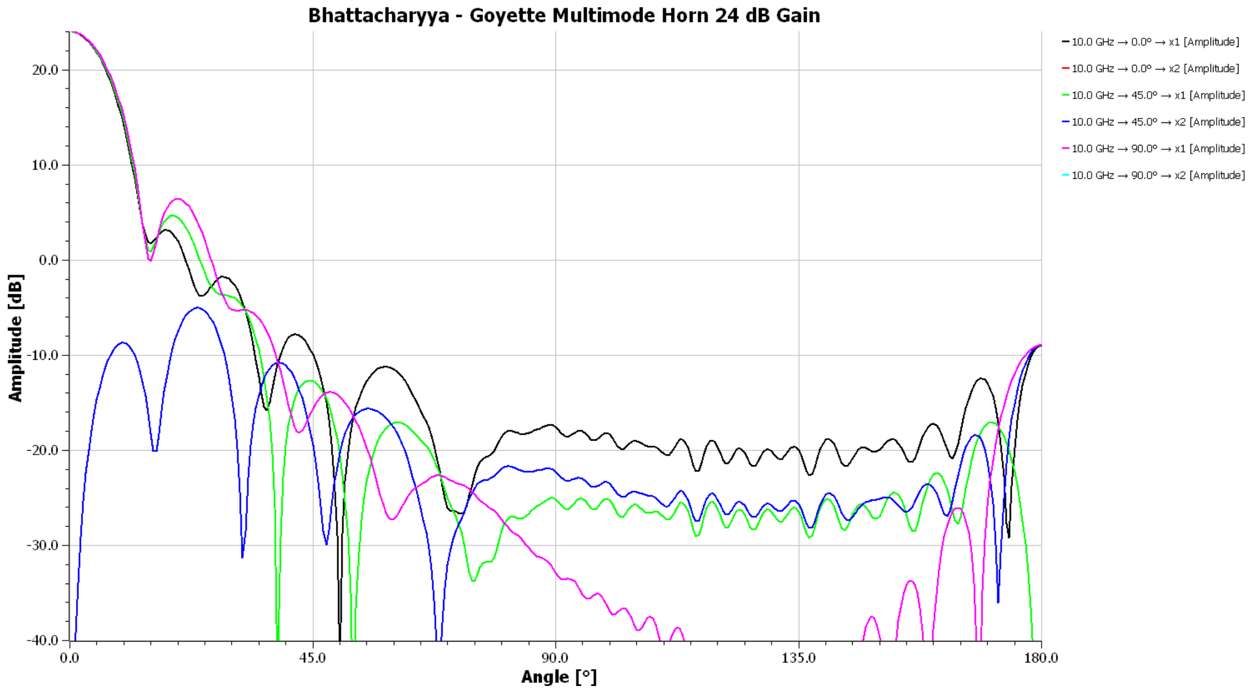


**Figure 7-9.4.25** Center frequency pattern of Bhattacharyya – Goyette Horn designed for 24 dB gain

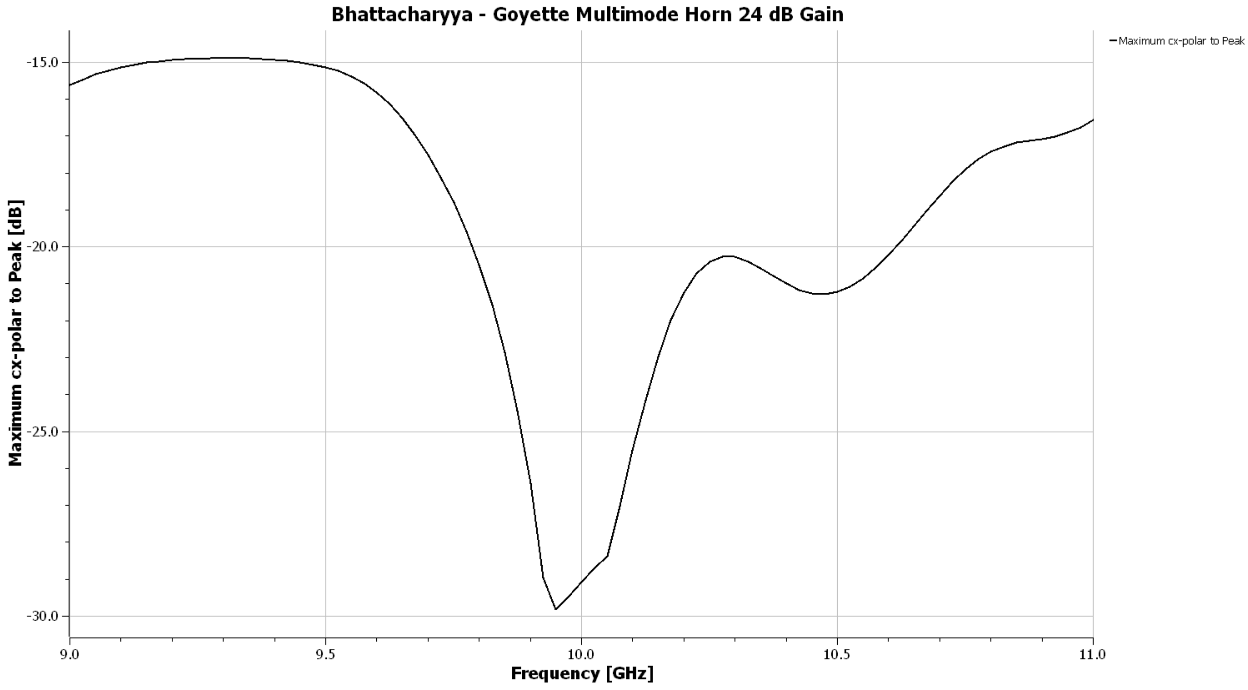


**Figure 7-9.4.26** Cross polarization response of Bhattacharyya – Goyette Horn designed for 24 dB gain

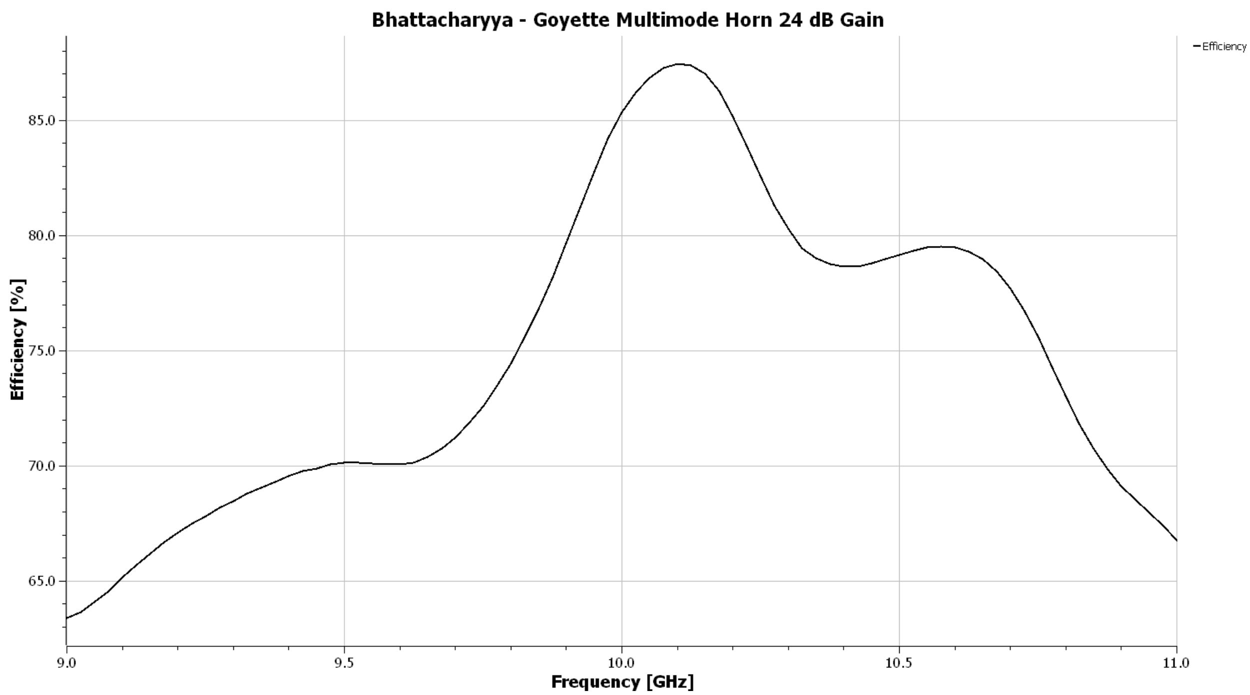


**Figure 7-9.4.27** Aperture efficiency of Bhattacharyya – Goyette Horn designed for 24 dB gain

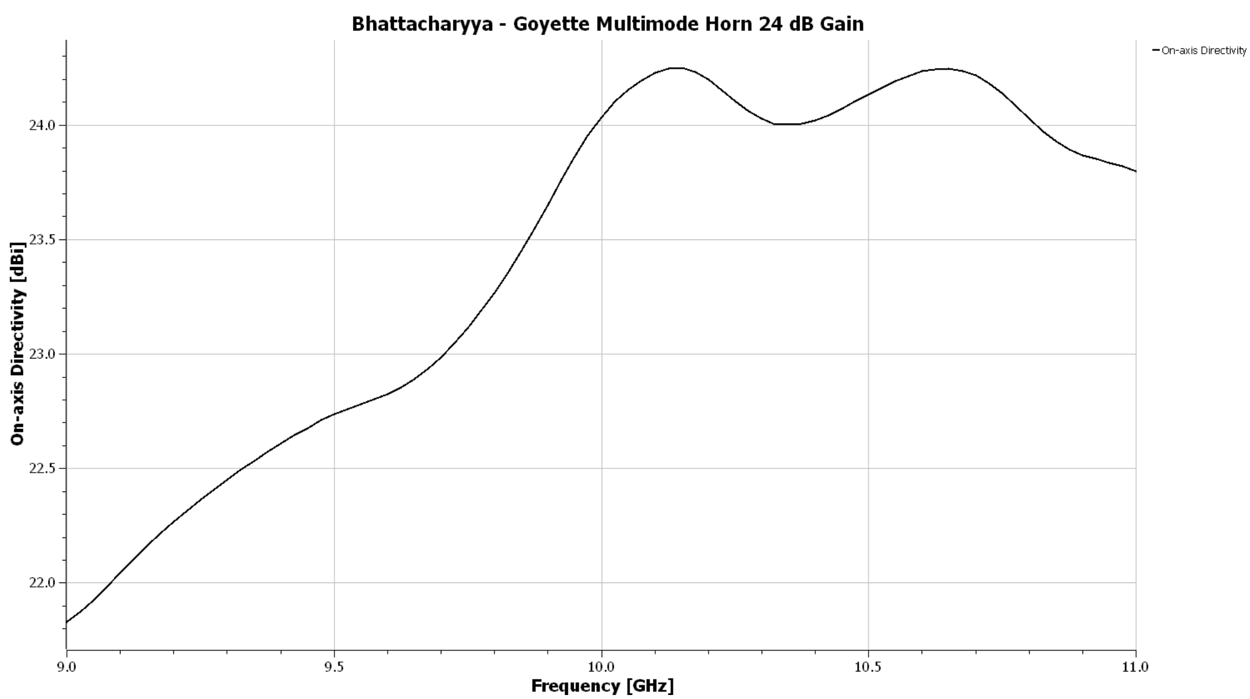


**Figure 7-9.4.28** On-axis Directivity of Bhattacharyya – Goyette Horn designed for 24 dB gain

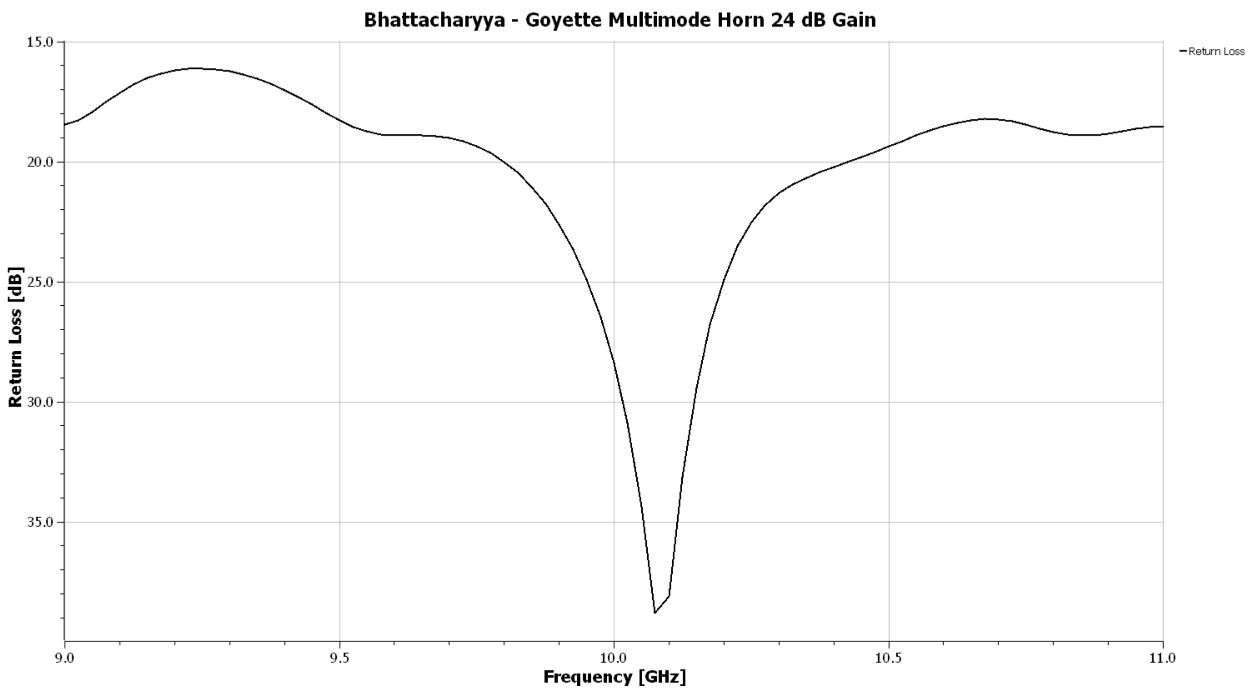


**Figure 7-9.4.29** Return Loss of Bhattacharyya – Goyette Horn designed for 24 dB gain

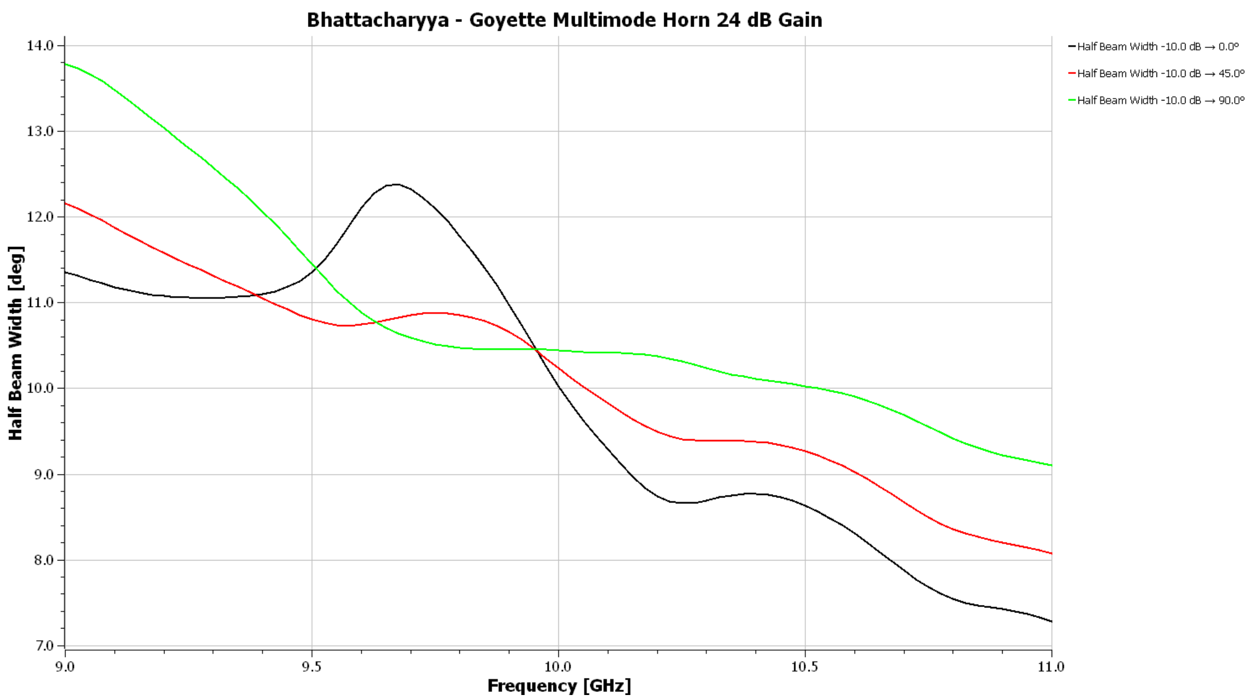


**Figure 7-9.4.30** 10 dB Half Beamwidth of Bhattacharyya – Goyette Horn designed for 24 dB gain

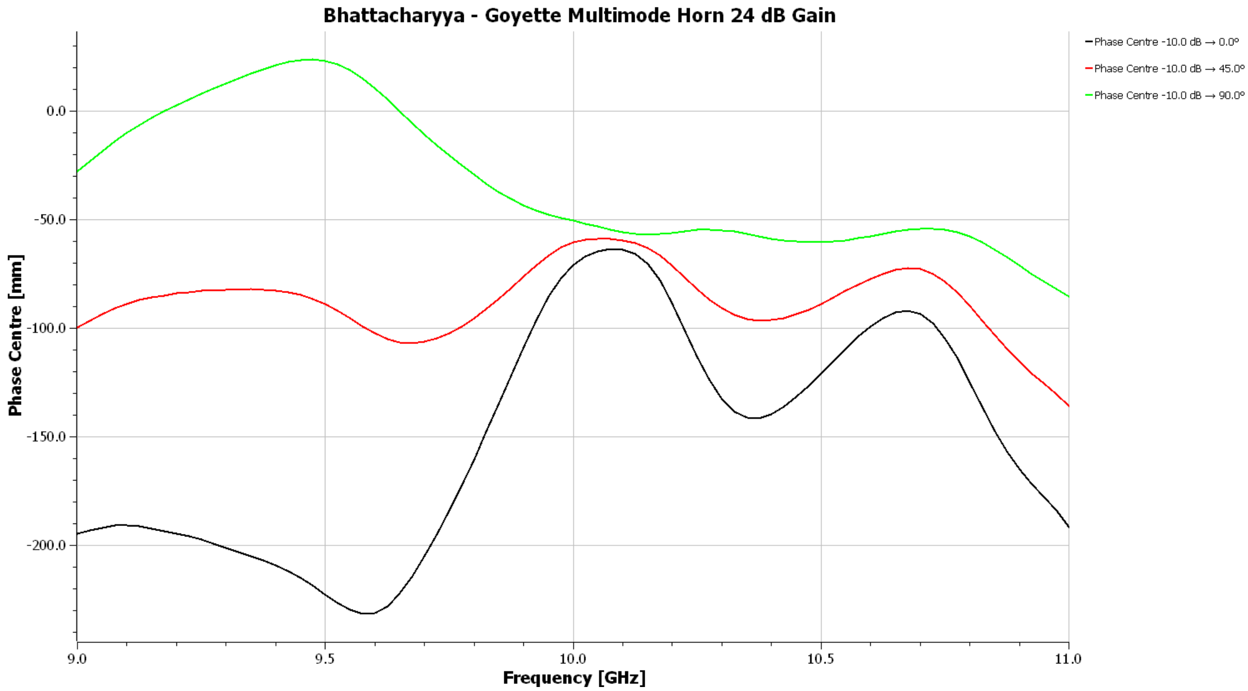


**Figure 7-9.4.31** 10 dB Phase Center of Bhattacharyya – Goyette Horn designed for 24 dB gain

The optimization frequency of the Bhattacharyya – Goyette horns was only 1% which produced narrow bandwidth return loss and cross polarization response with very good characteristics. A wider frequency range optimization could produce wider responses with lower values. Any optimization is a trade off.

## Chan – Rao Horns [3]

These horns reduce the $TM_{1j}$ modes in the radiating aperture by substituting slope changes in the bell to generate $TE_{1j}$ modes. When we inspect the modal response of these horns, we see that $TM_{1j}$ are generated.

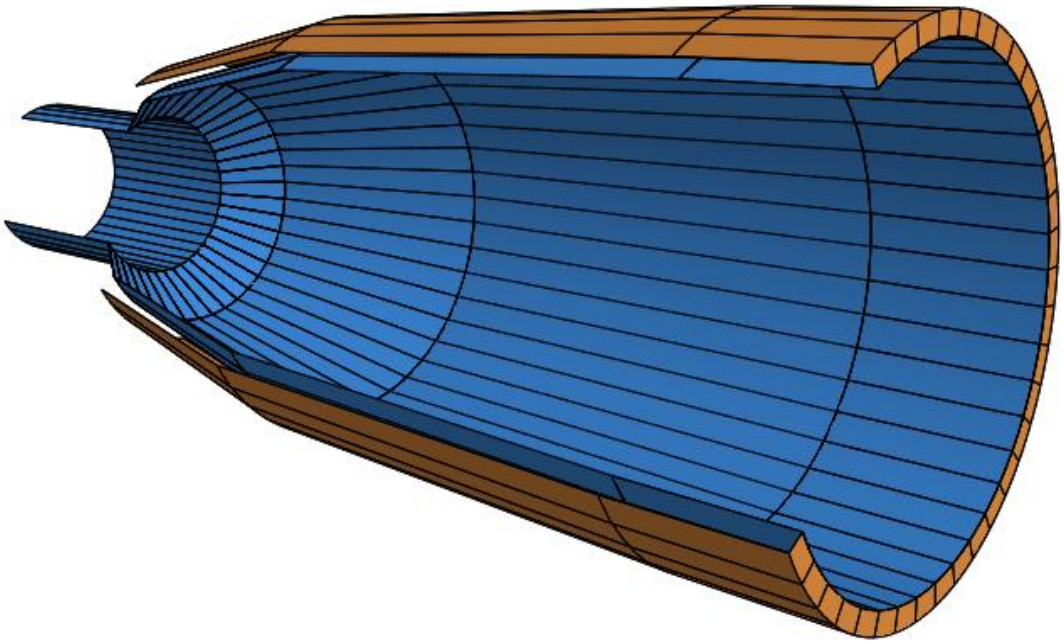

**Figure 7-9.4.32** Chan-Rao Horn designed for 16 dB

A series of horns were designed using the optimization in CHAMP (TICRA) to determine the internal diameters and lengths of tapered waveguide sections. These designs start with a feed waveguide diameter of 0.86727λ and an initial taper length of 0.30λ. Another set of designs used an initial taper of length 0.15λ but produced similar results. Table 7-9.4.4 gives the design dimensions of the diameters and tapered waveguide lengths for a series of designs. In this case the optimization frequency span is 4% which we will see produces wider bandwidth results.

**Table 7-9.4.4** Chan-Rao Tapered Sections High Efficiency Horns with initial Taper Length, L1 = 0.30λ with dimensions λ at the center frequency

| Gain | Aperture | Length | Efficiency | X-pol | L2 | L3 | L4 | D1 | D2 | D3 |
|---|---|---|---|---|---|---|---|---|---|---|
| 15.5 | 2.01779 | 4.4341 | 88.3 | -29.3 | 1.18405 | 2.04145 | 0.90863 | 1.30272 | 1.88796 | 1.98779 |
| 16.0 | 2.12416 | 4.5109 | 89.5 | -28.7 | 1.19282 | 2.23974 | 0.78736 | 1.31768 | 1.87254 | 1.98416 |
| 16.5 | 2.25908 | 4.6092 | 88.6 | -27.7 | 1.01932 | 2.28031 | 1.00960 | 1.31958 | 1.78136 | 2.22908 |
| 17.0 | 2.40685 | 4.5763 | 87.7 | -27.6 | 0.93858 | 2.28701 | 1.05075 | 1.32572 | 1.73025 | 2.37685 |
| 17.5 | 2.53293 | 4.5934 | 89.0 | -27.2 | 0.83685 | 2.33882 | 1.11775 | 1.33539 | 1.68110 | 2.50293 |
| 18.0 | 2.67653 | 4.4348 | 89.0 | -28.8 | 0.78085 | 1.98017 | 1.37382 | 1.45247 | 1.53151 | 2.64653 |
| 18.5 | 2.80108 | 4.4679 | 92.0 | -31.3 | 0.75434 | 1.93742 | 1.47614 | 1.45481 | 1.44893 | 2.75667 |
| 19.0 | 3.00886 | 4.4357 | 88.9 | -28.6 | 0.78421 | 1.85731 | 1.49422 | 1.46436 | 1.46967 | 2.91956 |
| 19.5 | 3.18819 | 4.3653 | 88.6 | -28.8 | 0.72118 | 1.99175 | 1.35240 | 1.42217 | 1.44163 | 3.10991 |
| 20.0 | 3.38918 | 4.2918 | 88.1 | -27.3 | 0.78091 | 1.93861 | 1.27231 | 1.41715 | 1.52281 | 3.19098 |
| 20.5 | 3.57983 | 4.7721 | 88.7 | -27.5 | 0.83868 | 2.09931 | 1.53408 | 1.47185 | 1.51556 | 3.44476 |
| 21.0 | 3.80800 | 5.2486 | 87.7 | -26.8 | 0.88645 | 2.00809 | 2.05408 | 1.49804 | 1.53257 | 3.60654 |
| 21.5 | 4.03918 | 5.7149 | 88.0 | -26.4 | 0.89288 | 2.57561 | 1.95640 | 1.47998 | 1.58814 | 3.82335 |
| 22.0 | 4.29257 | 5.9581 | 87.6 | -27.0 | 1.00057 | 2.51131 | 2.41627 | 1.45974 | 1.66260 | 3.88507 |
| 22.5 | 4.61268 | 6.2348 | 84.4 | -24.5 | 0.93969 | 2.39482 | 2.60032 | 1.50915 | 1.63024 | 3.89936 |
| 23.0 | 4.85279 | 7.1976 | 85.9 | -24.7 | 1.06971 | 2.48120 | 3.34672 | 1.54176 | 1.64378 | 3.93737 |
| 23.5 | 5.18326 | 8.2362 | 84.5 | -23.0 | 1.26246 | 2.95309 | 3.72068 | 1.48057 | 1.92656 | 4.15784 |
| 24.0 | 5.44808 | 9.0722 | 86.0 | -22.2 | 1.41394 | 3.15438 | 4.20384 | 1.54155 | 1.97482 | 4.39813 |

**Table 7-9.4.5** Chan-Rao Tapered Sections High Efficiency Horns with initial Taper Length, L1 = 0.30λ Aperture Radiating Mode Amplitudes dB

| Gain | TE(1) | TE(2) | TE(3) | TE(4) | TE(5) | TE(6) | TM(1) | TM(2) | TM(3) | TM(4) | TM(5) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 15.5 | -0.22 | -26.41 | | | | | -13.49 | | | | |
| 16.0 | -0.19 | -23.99 | | | | | -14.43 | | | | |
| 16.5 | -0.16 | -25.70 | | | | | -14.84 | -32.22 | | | |
| 17.0 | -0.18 | -24.50 | | | | | -14.94 | -23.99 | | | |
| 17.5 | -0.17 | -22.76 | | | | | -14.65 | -27.72 | | | |
| 18.0 | -0.21 | -18.66 | | | | | -15.64 | -23.28 | | | |
| 18.5 | -0.31 | -15.81 | -27.60 | | | | -13.96 | -29.91 | | | |
| 19.0 | -0.30 | -14.41 | -27.50 | | | | -16.15 | -24.61 | | | |
| 19.5 | -0.44 | -12.90 | -28.90 | | | | -14.08 | -22.98 | | | |
| 20.0 | -0.49 | -12.07 | -33.59 | | | | -13.78 | -24.67 | -25.01 | | |
| 20.5 | -0.56 | -10.81 | -27.19 | | | | -15.35 | -27.20 | -28.41 | | |
| 21.0 | -0.75 | -9.54 | -24.56 | -41.13 | | | -15.78 | -22.85 | -23.15 | | |
| 21.5 | -0.65 | -10.64 | -26.34 | -36.05 | | | -14.72 | -21.38 | -27.11 | | |
| 22.0 | -0.64 | -10.32 | -31.93 | -33.11 | | | -15.25 | -21.89 | -28.99 | -30.89 | |
| 22.5 | -0.67 | -10.14 | -38.68 | -31.20 | | | -15.61 | -25.32 | -21.61 | -26.43 | |
| 23.0 | -0.59 | -10.87 | -28.88 | -38.58 | | | -15.62 | -21.14 | -25.92 | -31.05 | |
| 23.5 | -0.51 | -12.17 | -27.78 | -37.82 | -41.59 | | -14.24 | -28.88 | -20.79 | -31.36 | |
| 24.0 | -0.47 | -12.35 | -27.31 | -35.94 | -42.38 | | -15.86 | -23.79 | -20.08 | -28.99 | -32.25 |

Table 7-9.4.5 of the Chan-Rao horns shows little difference in aperture mode levels from those in Table 7-9.4.3 of the optimized Bhattacharyya – Goyette horns. Both produce TM modes which radiate cross polarization. The levels of the TE modes are not the optimum to produce better aperture efficiency.  However, both designs produce nearly hard horn responses over narrow bandwidths.

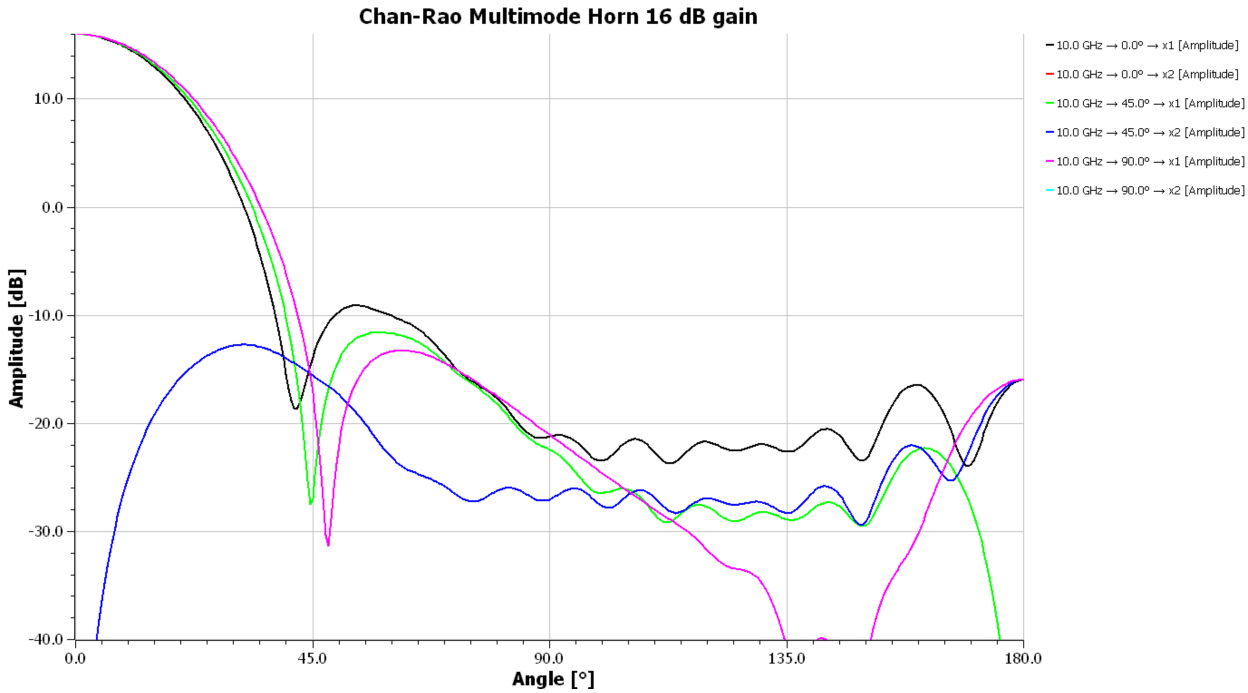


**Figure 7-9.4.33** Center frequency pattern of Chan-Rao Horn designed for 16 dB gain

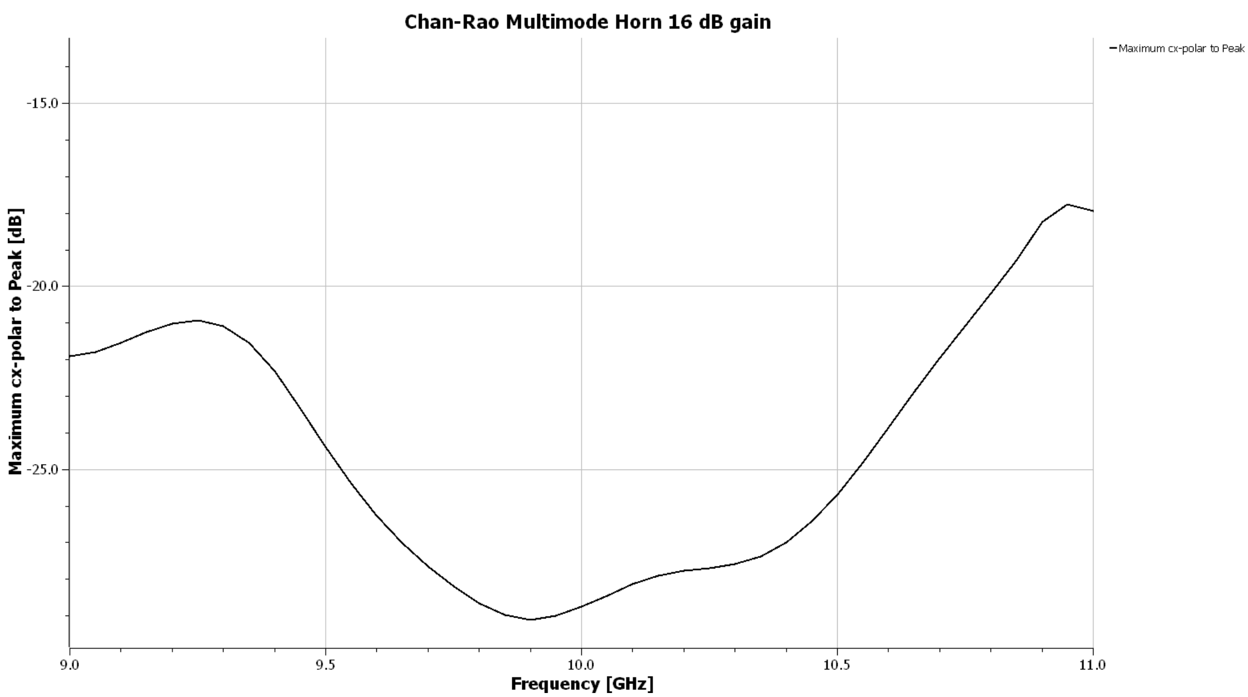


**Figure 7-9.4.34** Cross polarization response of Chan-Rao Horn designed for 16 dB gain

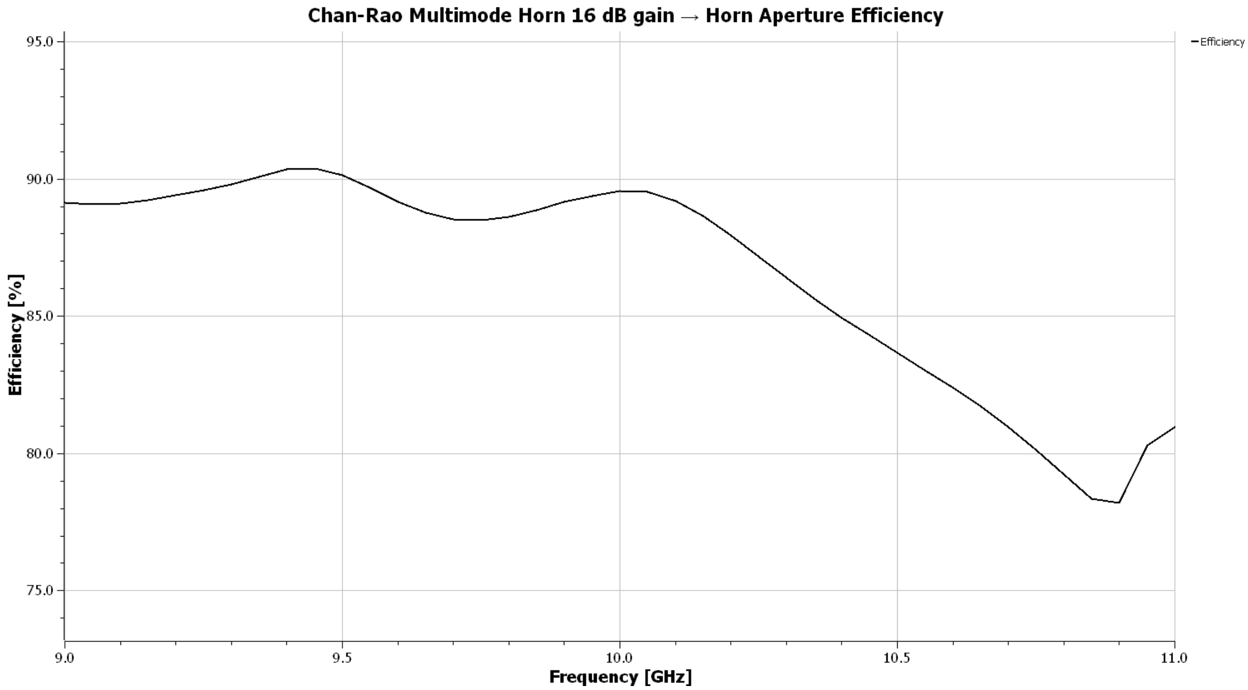


**Figure 7-9.4.35** Aperture efficiency of Chan-Rao Horn designed for 16 dB gain

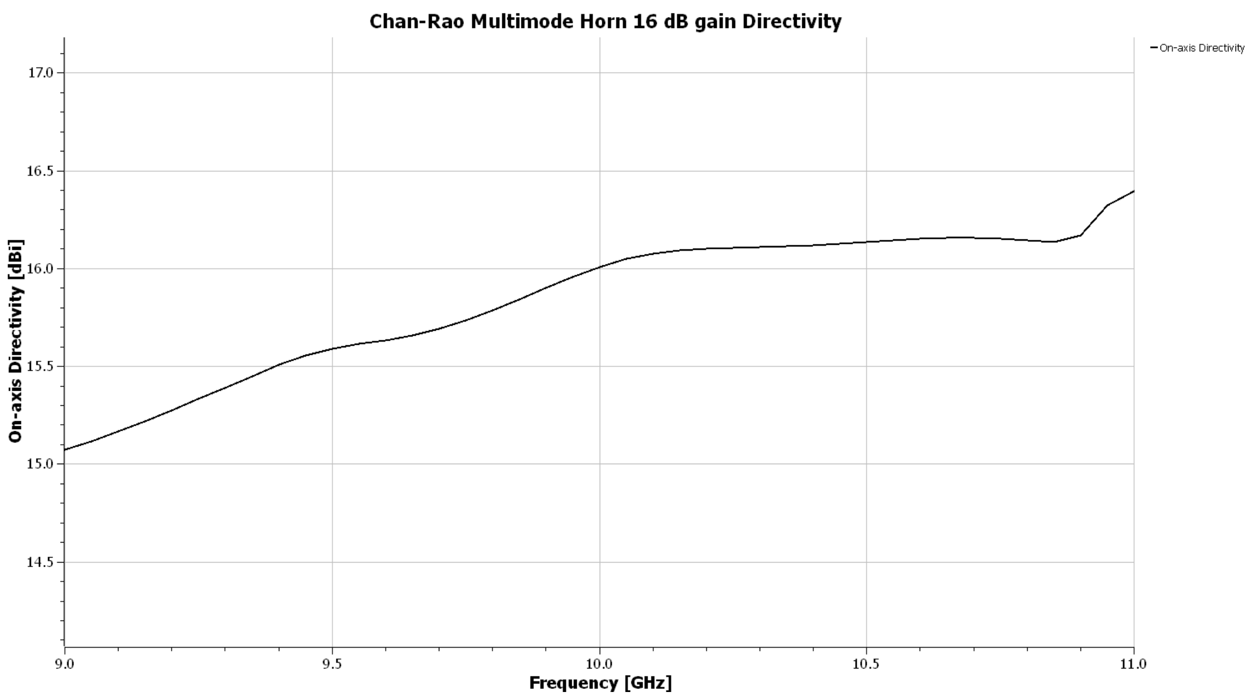


**Figure 7-9.4.36** On-axis Directivity of Chan-Rao Horn designed for 16 dB gain

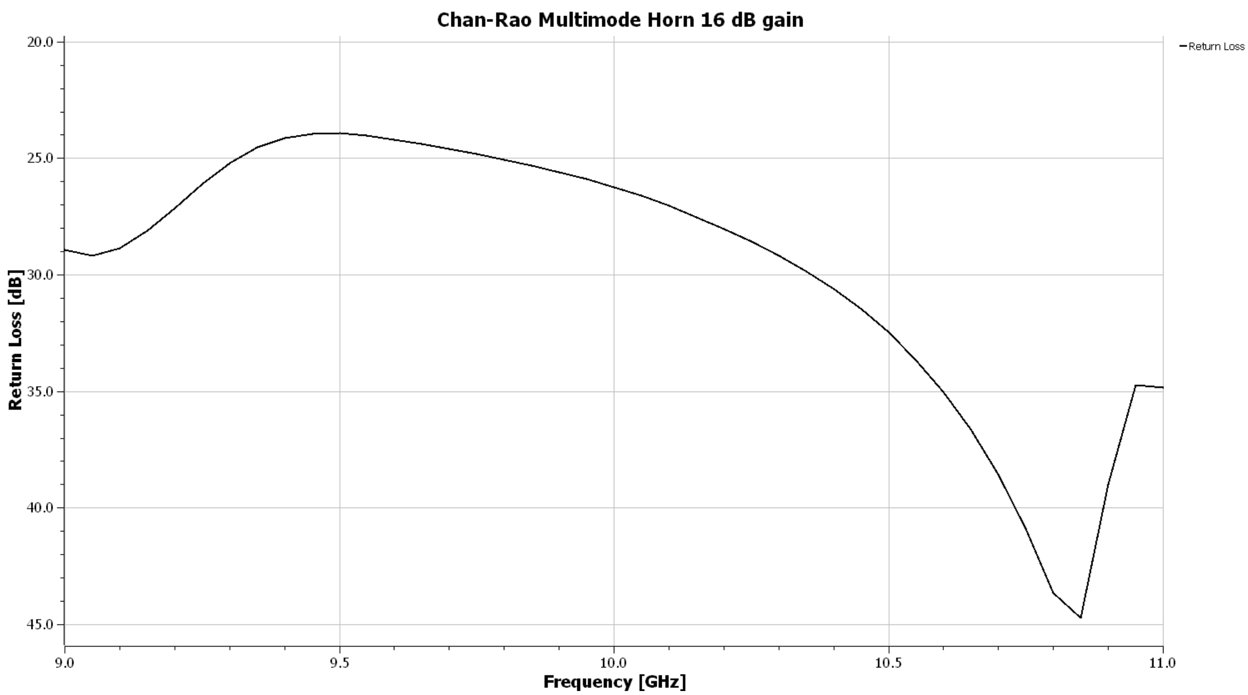


**Figure 7-9.4.37** Return Loss of Chan-Rao Horn designed for 16 dB gain

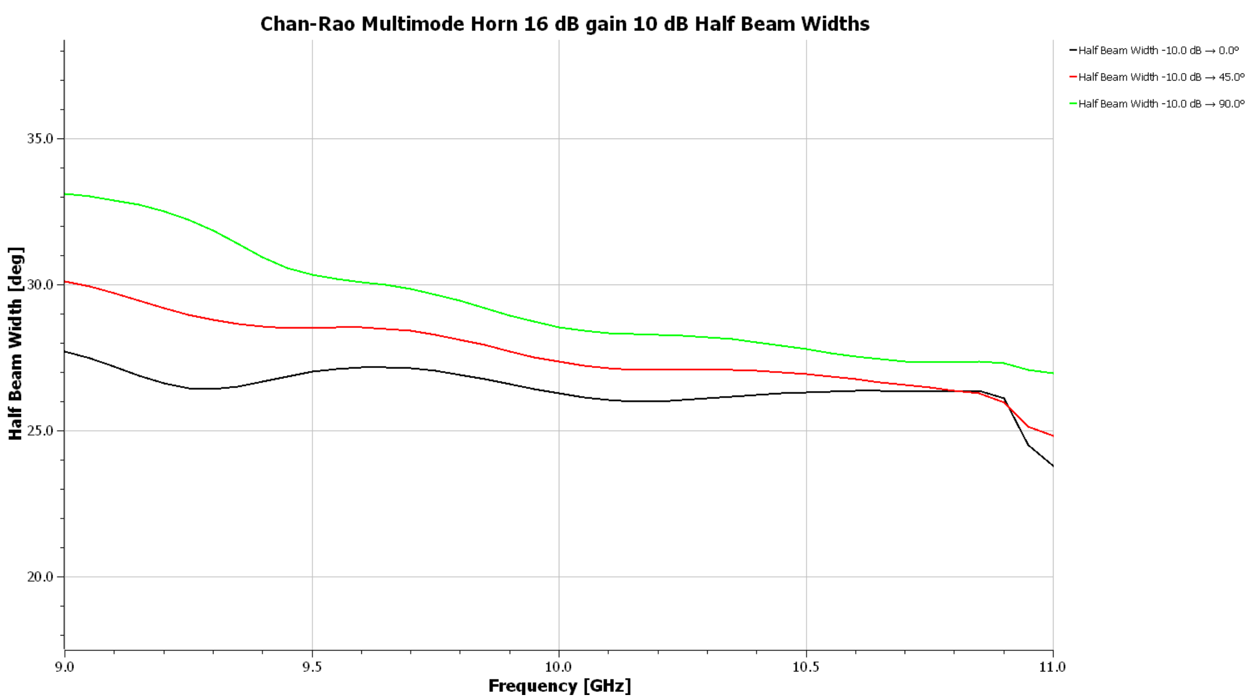


**Figure 7-9.4.38** 10 dB Half Beamwidth of Chan-Rao Horn designed for 16 dB gain

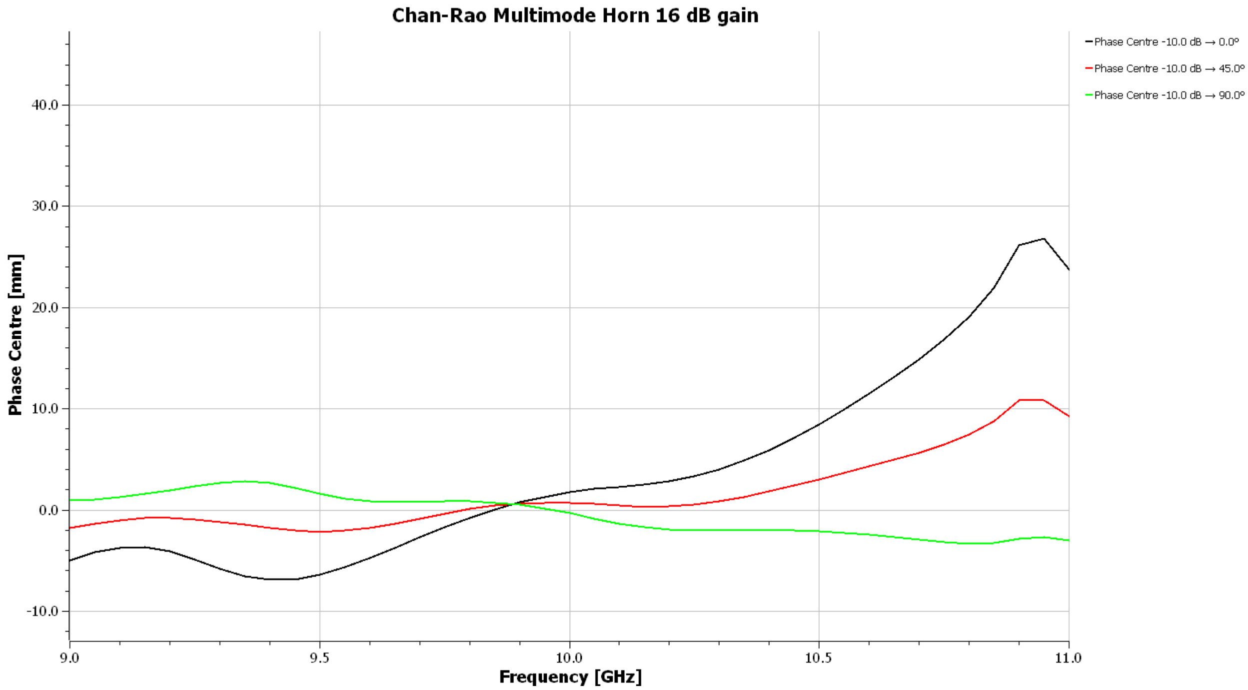


**Figure 7-9.4.39** 10 dB Phase Center of Chan-Rao Horn designed for 16 dB gain

## 20 dB Gain Chan-Rao High Aperture Efficiency Horn

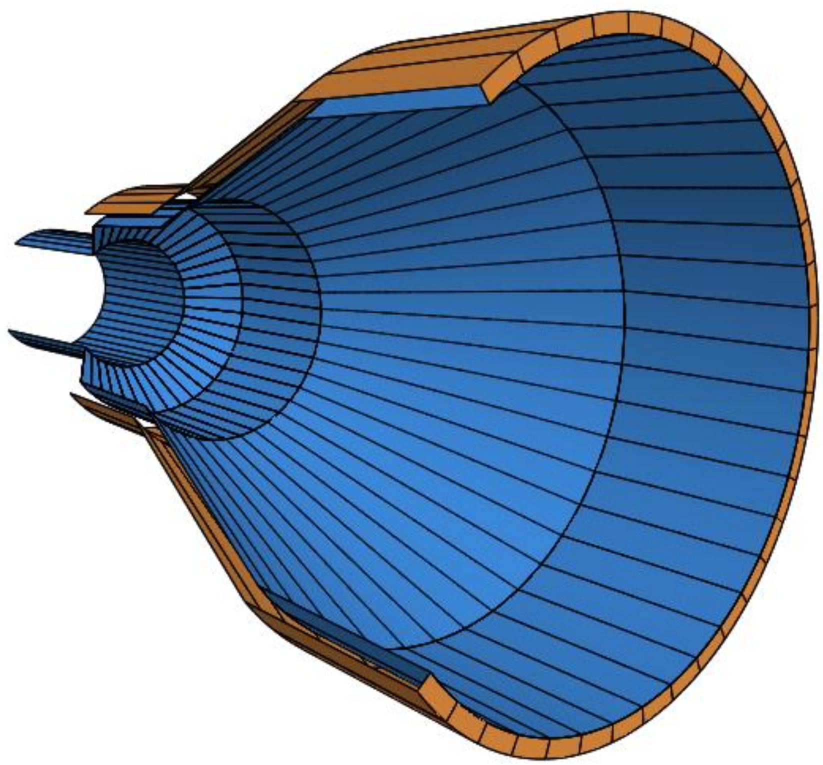

**Figure 7-9.4.40** Chan-Rao Horn designed for 20 dB

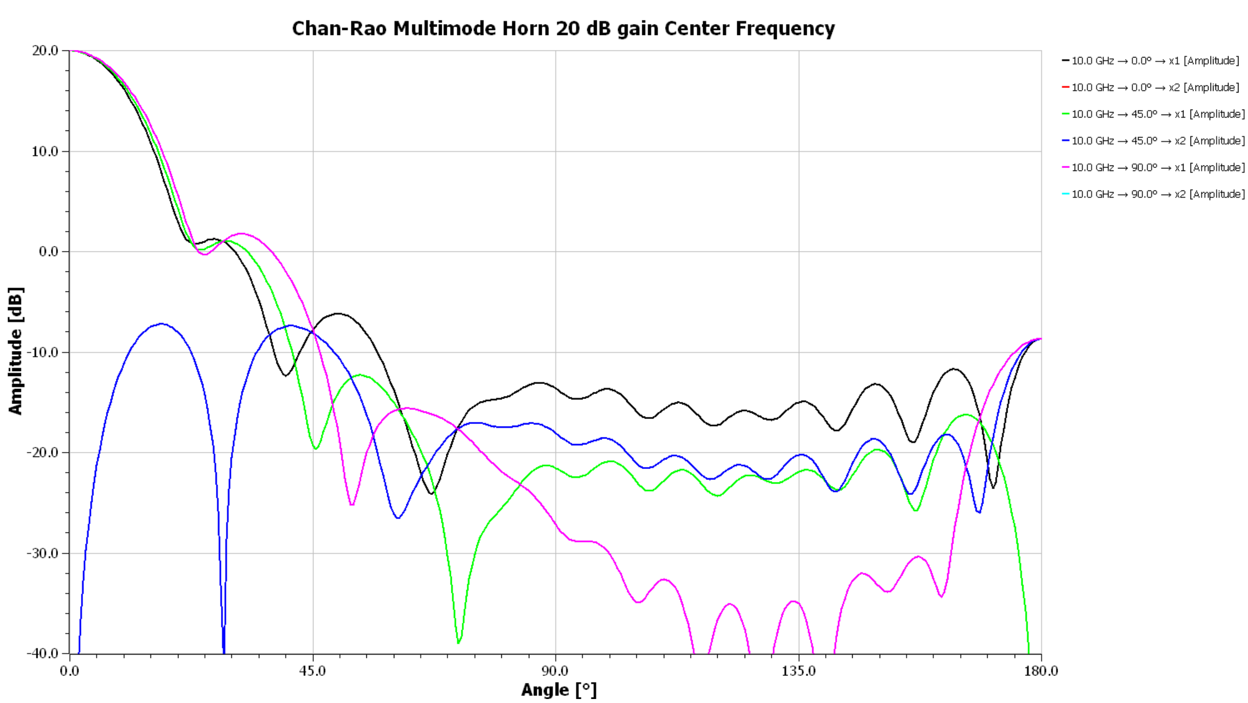

**Figure 7-9.4.41** Center frequency pattern of Chan-Rao Horn designed for 20 dB gain

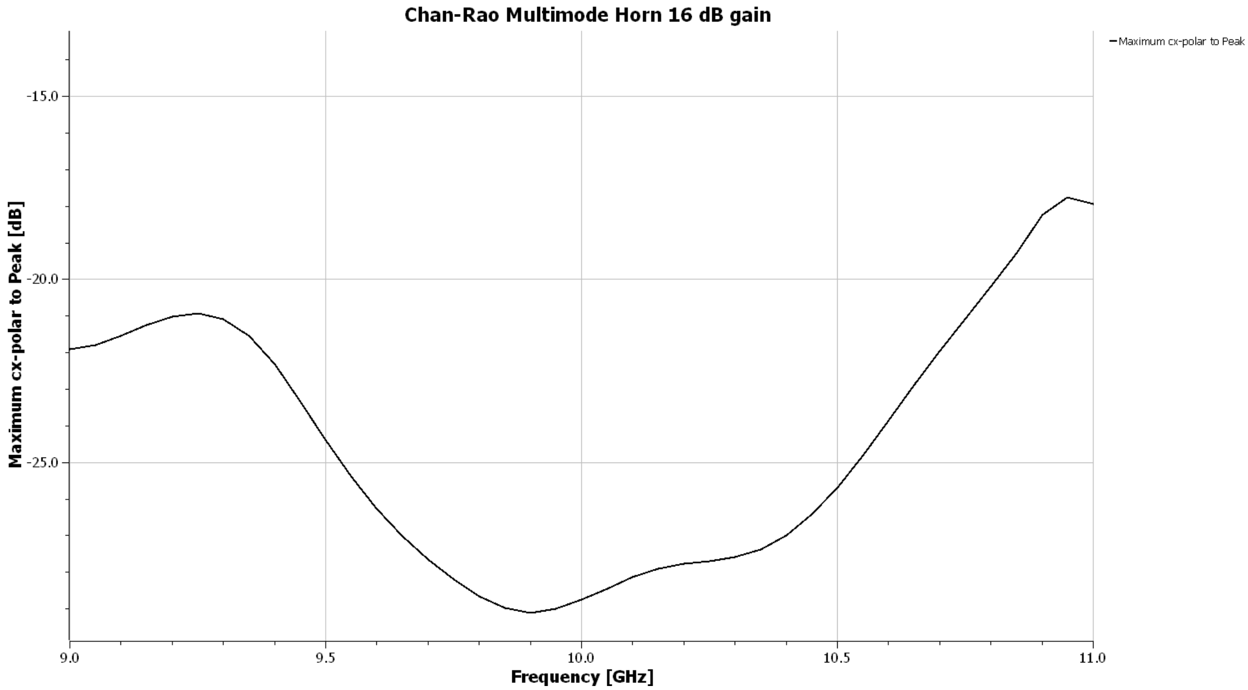


**Figure 7-9.4.42** Cross polarization response of Chan-Rao Horn designed for 20 dB gain

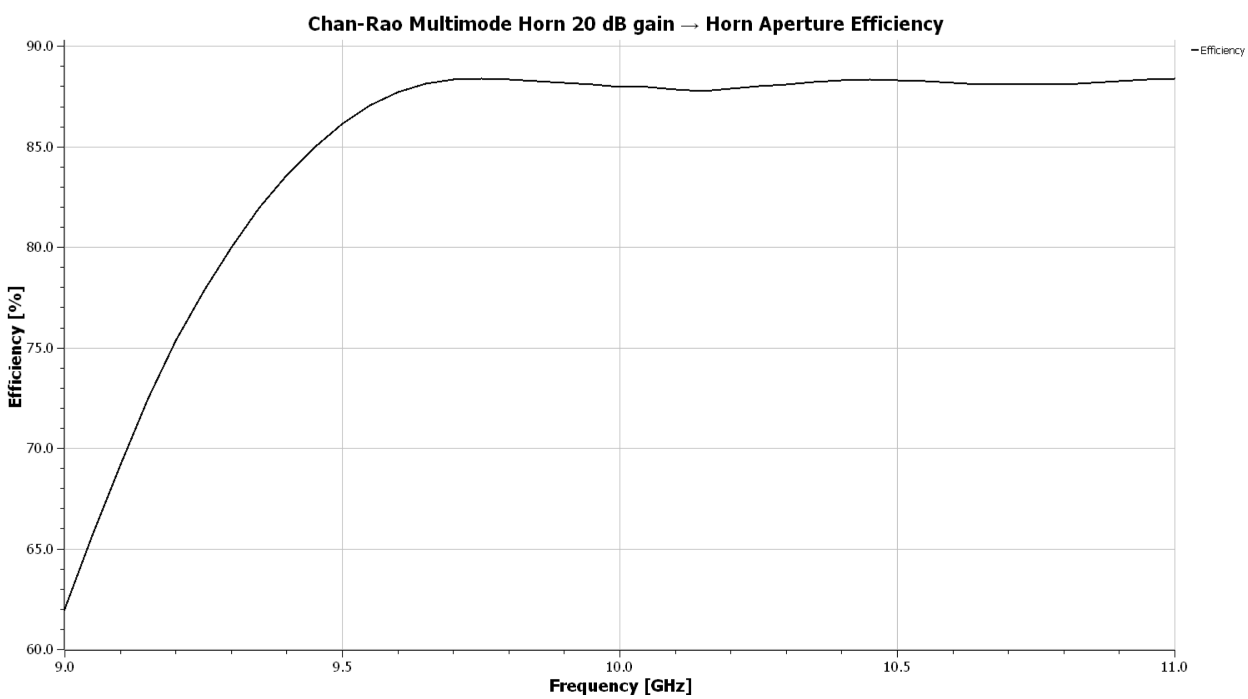


**Figure 7-9.4.43** Aperture efficiency of Chan-Rao Horn designed for 20 dB gain

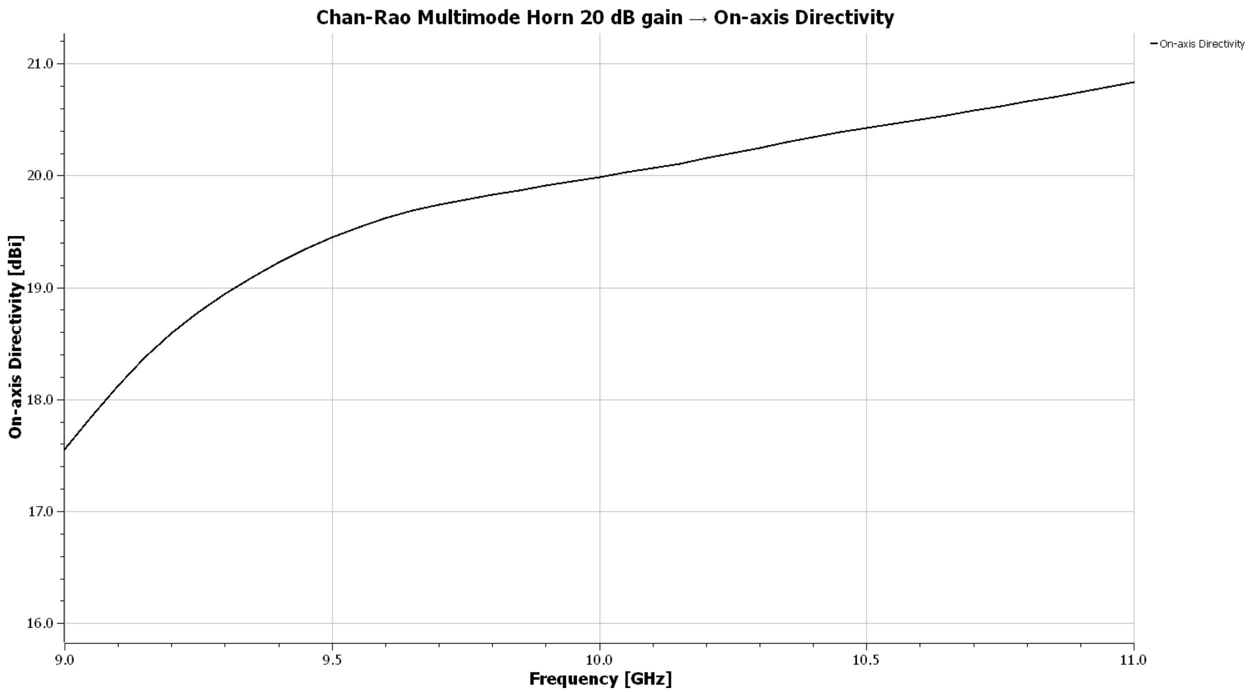


**Figure 7-9.4.44** On-axis Directivity of Chan-Rao Horn designed for 20 dB gain

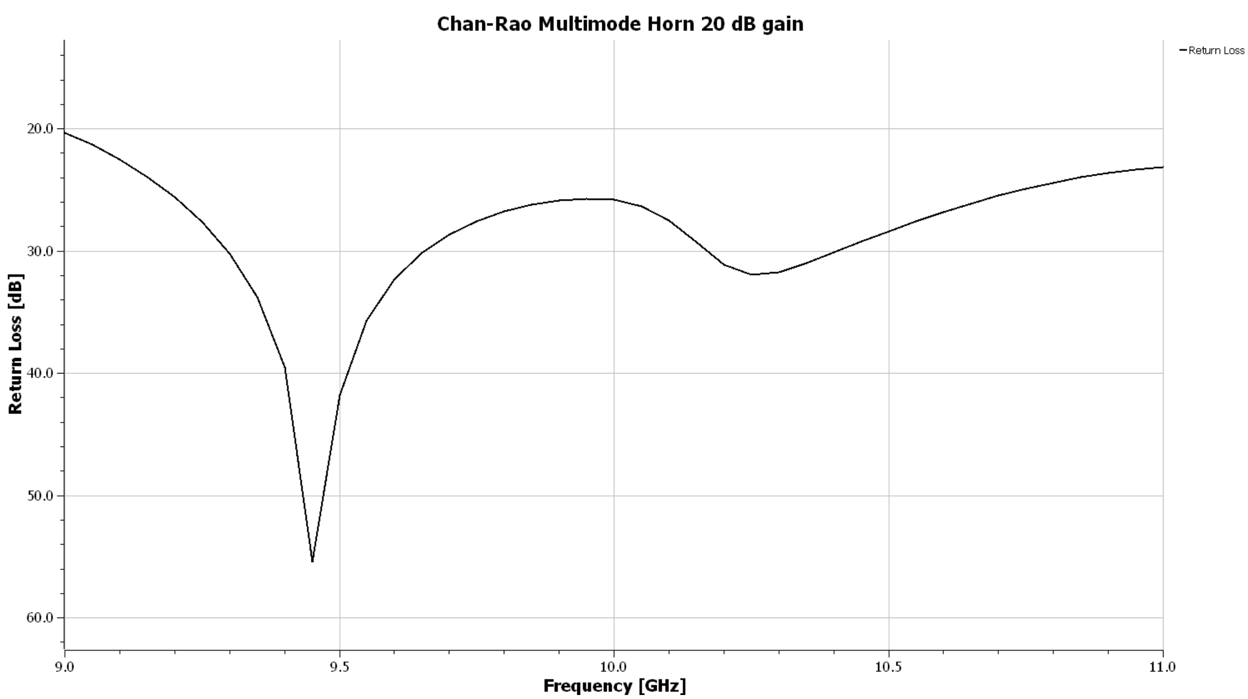


**Figure 7-9.4.45** Return Loss of Chan-Rao Horn designed for 20 dB gain

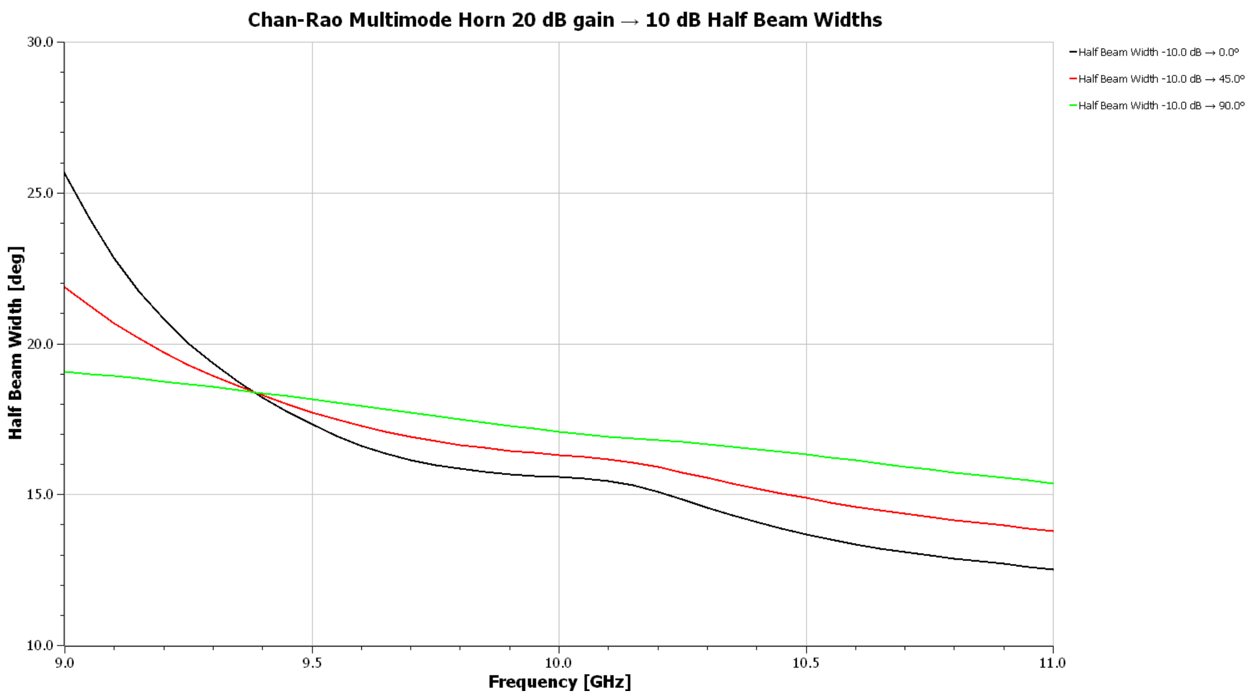


**Figure 7-9.4.46** 10 dB Half Beamwidth of Chan-Rao Horn designed for 20 dB gain

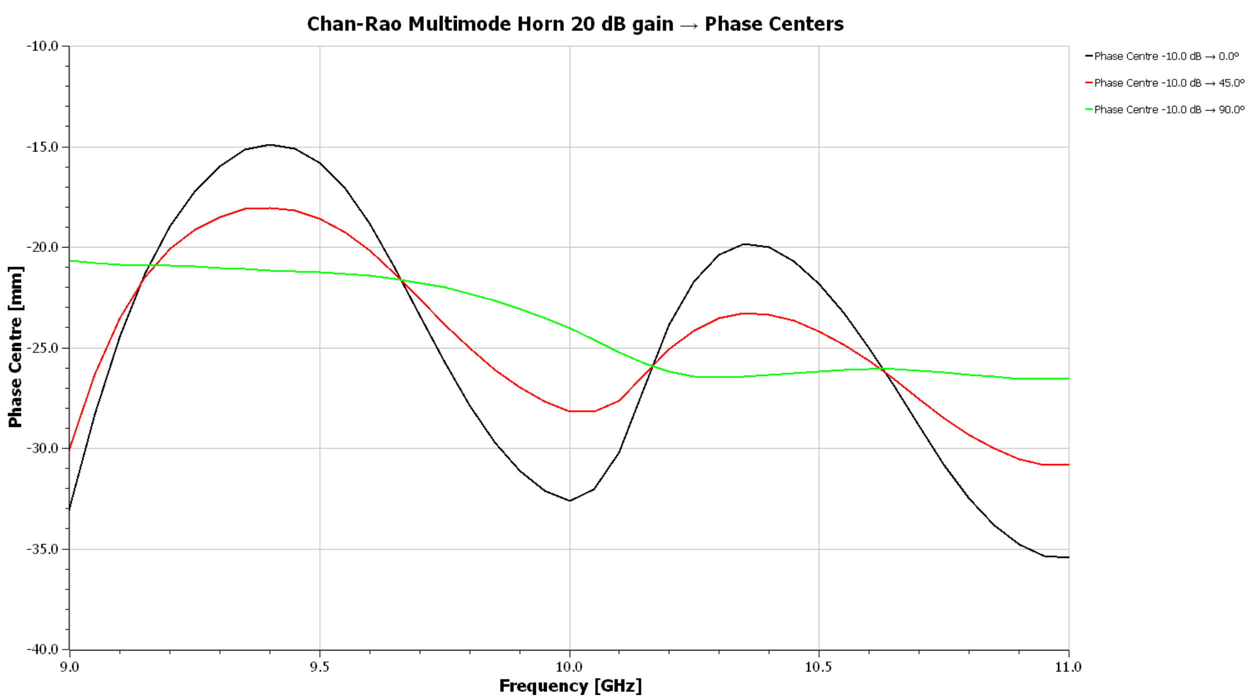


**Figure 7-9.4.47** 10 dB Phase Center of Chan-Rao Horn designed for 20 dB gain

## 24 dB Gain Chan-Rao High Aperture Efficiency Horn

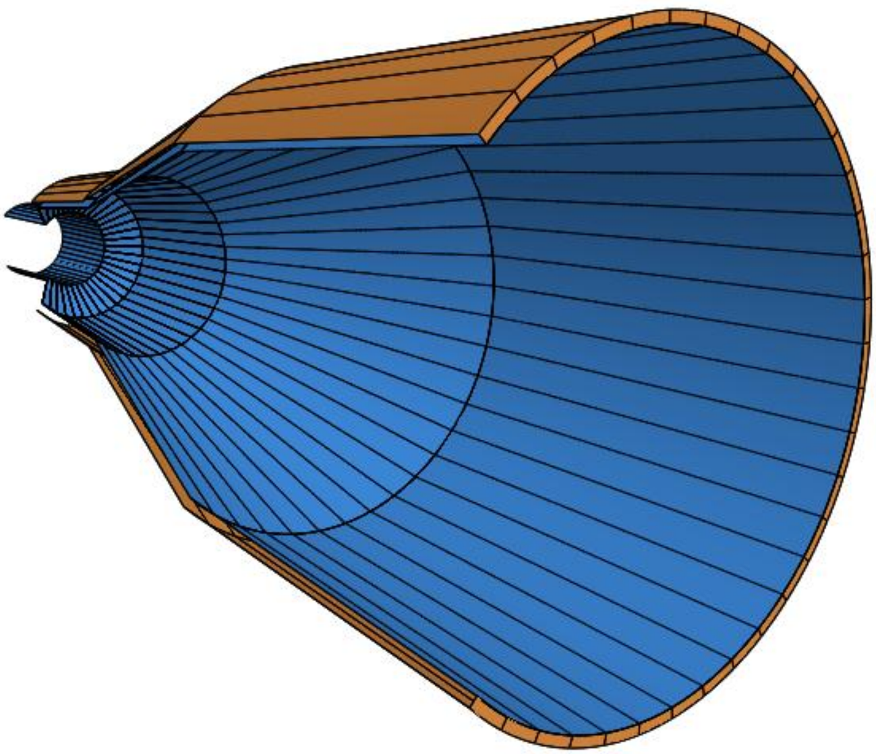

**Figure 7-9.4.48** Chan-Rao Horn designed for 24 dB

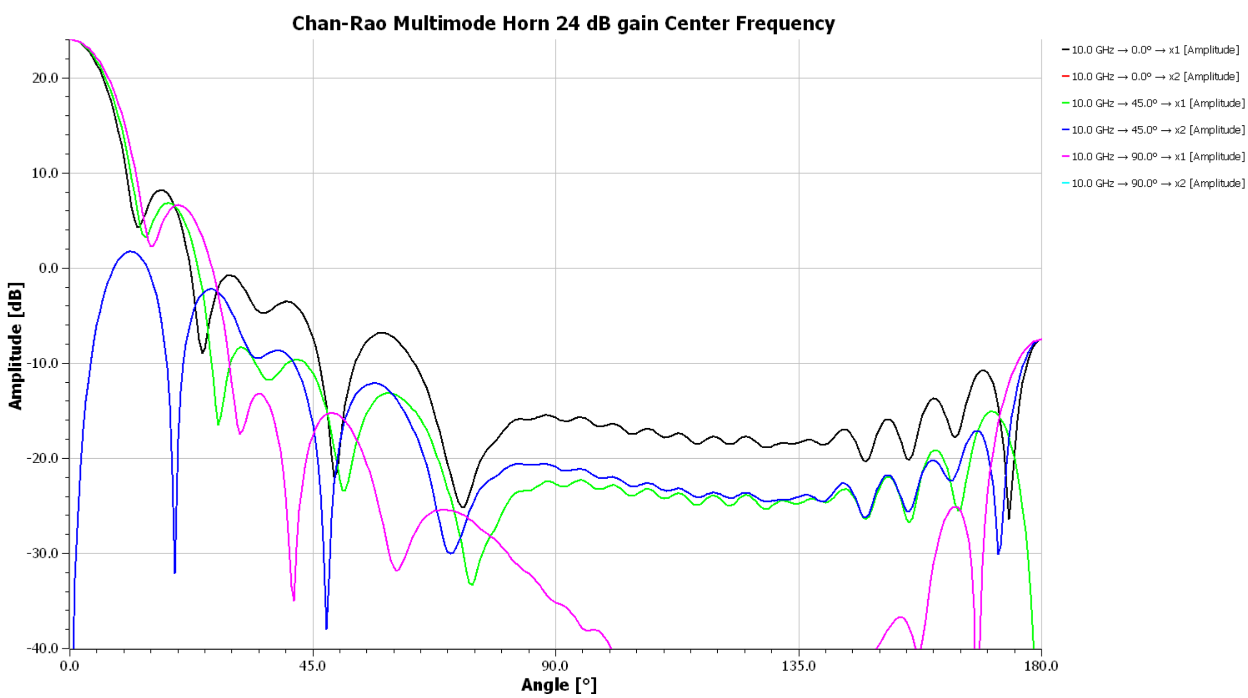

**Figure 7-9.4.49** Center frequency pattern of Chan-Rao Horn designed for 24 dB gain

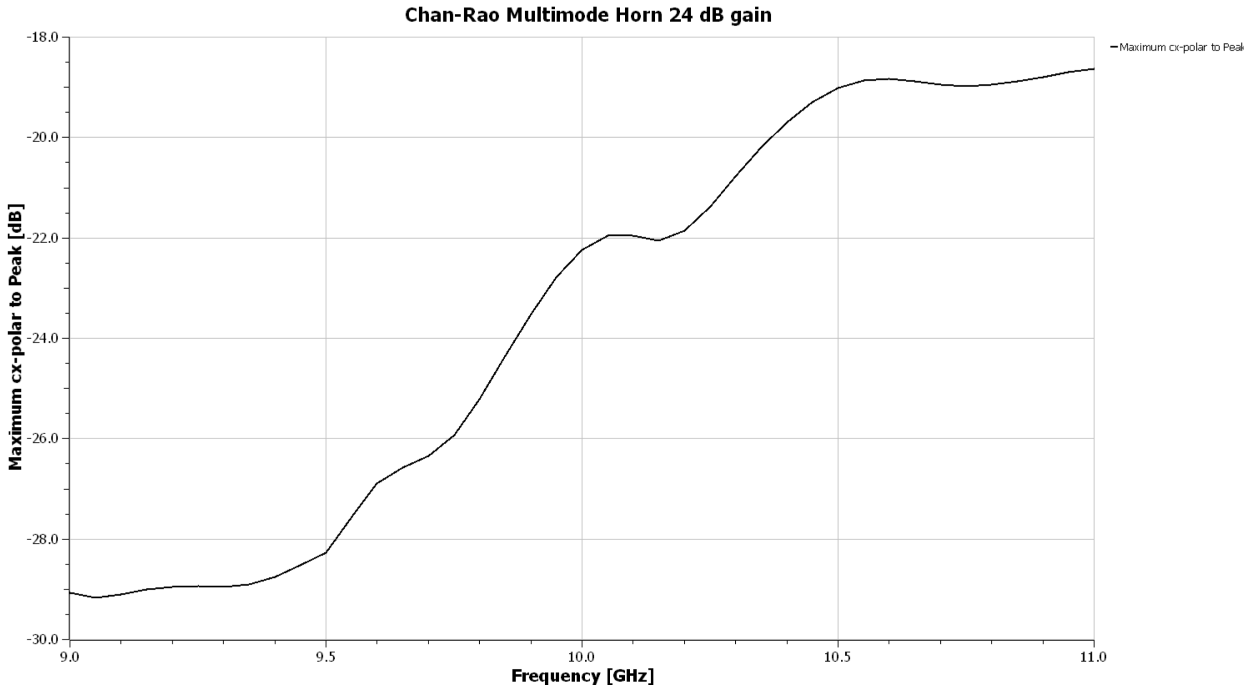


**Figure 7-9.4.50** Cross polarization response of Chan-Rao Horn designed for 24 dB gain

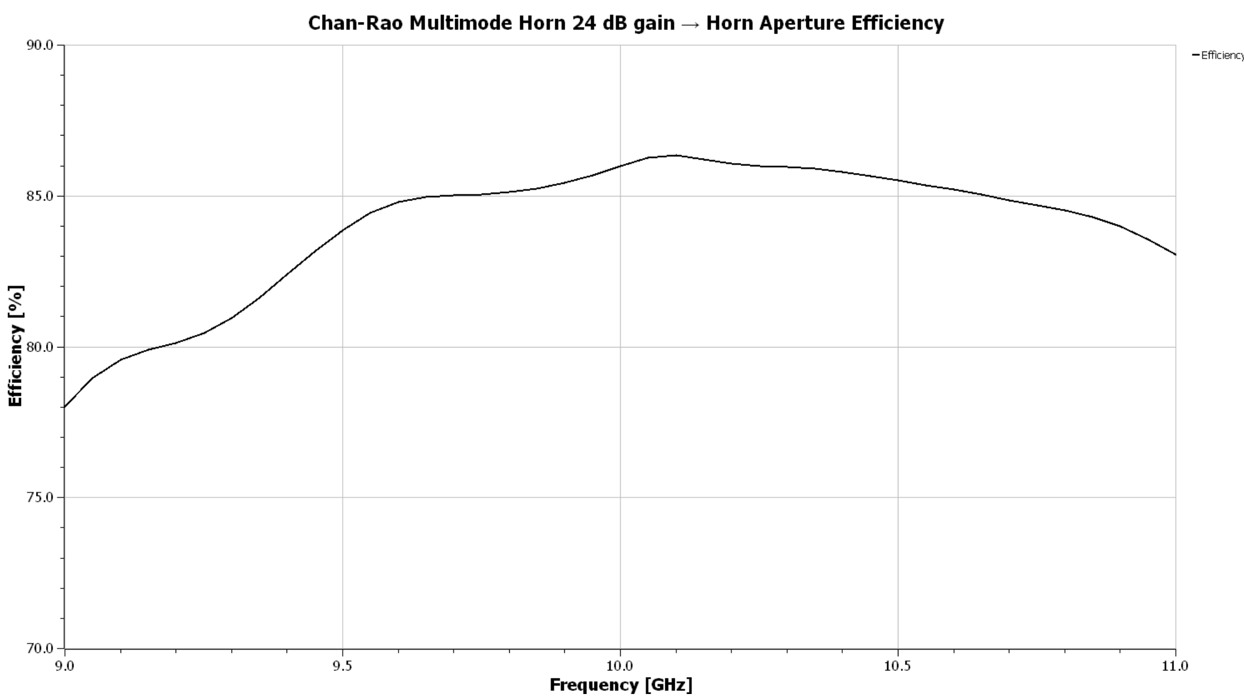


**Figure 7-9.4.51** Aperture efficiency of Chan-Rao Horn designed for 24 dB gain

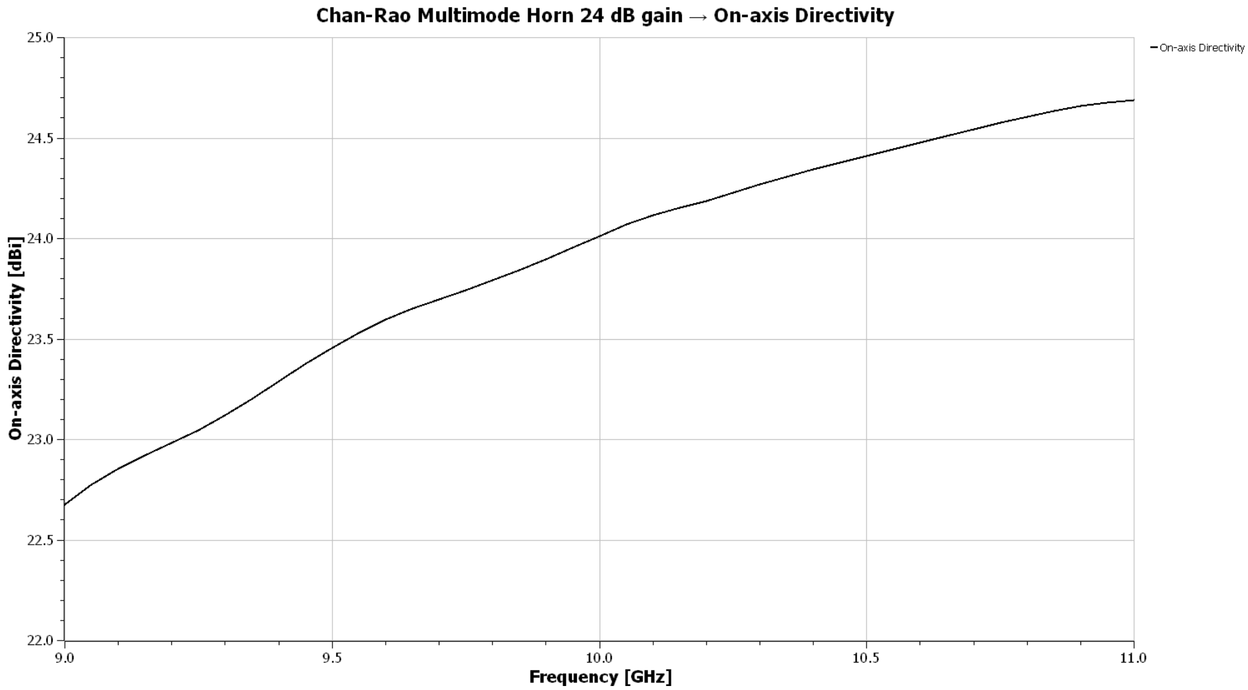


**Figure 7-9.4.52** On-axis Directivity of Chan-Rao Horn designed for 24 dB gain

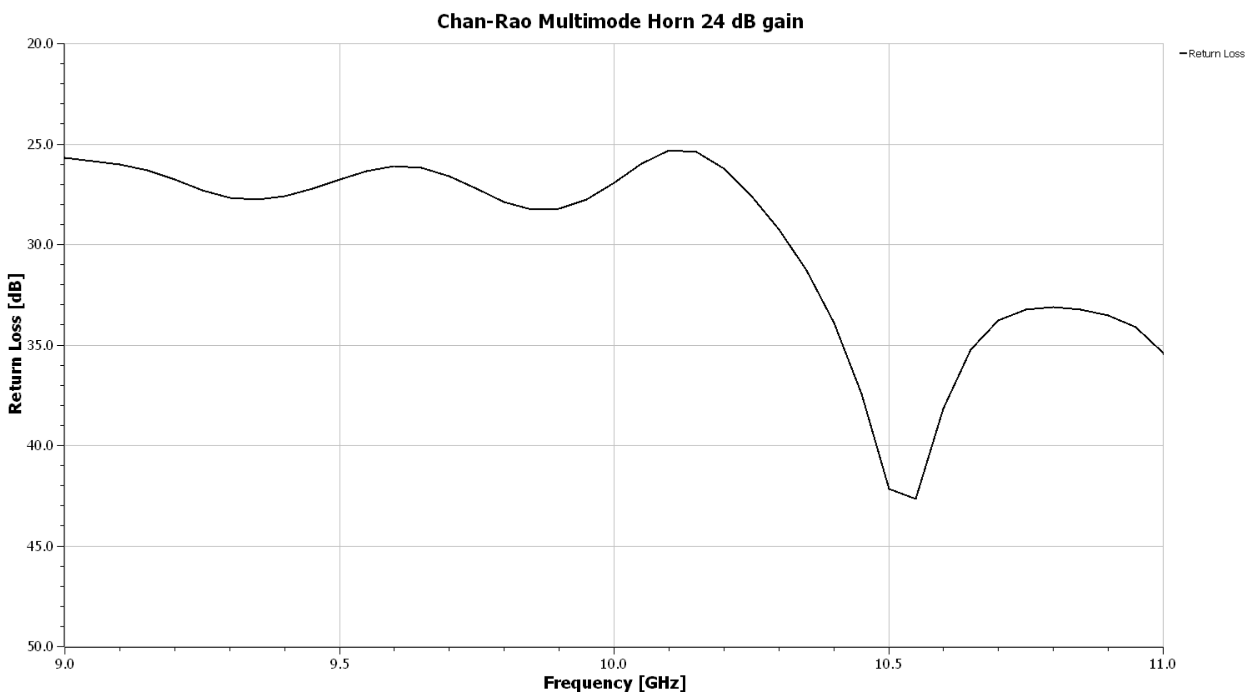


**Figure 7-9.4.53** Return Loss of Chan-Rao Horn designed for 24 dB gain

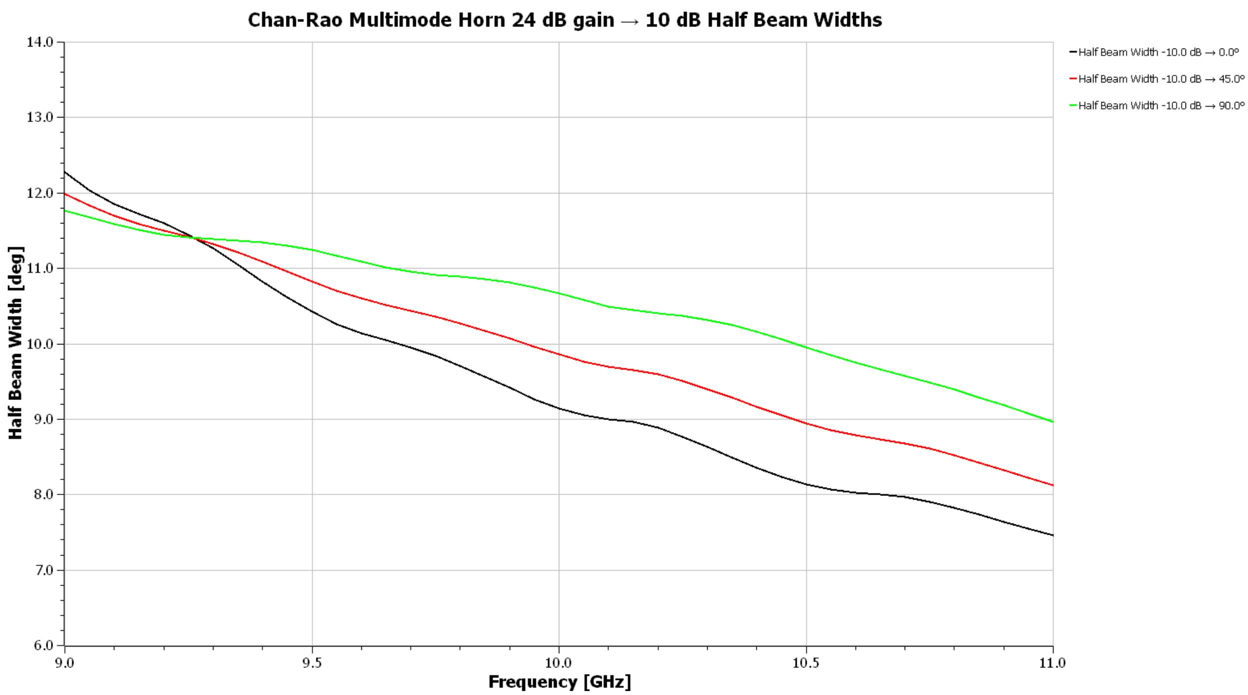


**Figure 7-9.4.54** 10 dB Half Beamwidth of Chan-Rao Horn designed for 24 dB gain

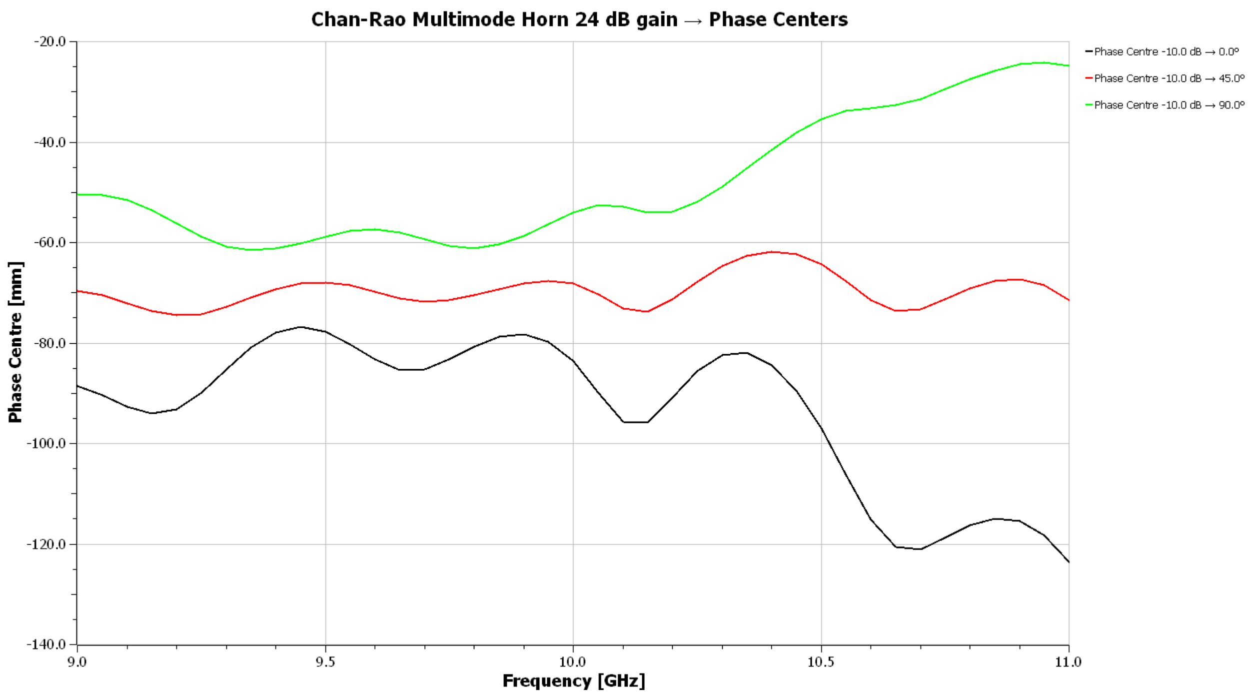


**Figure 7-9.4.55** 10 dB Phase Center of Chan-Rao Horn designed for 24 dB gain

## 16.5 dB Gain Chan-Rao High Aperture Efficiency Horn w/ Long Bell

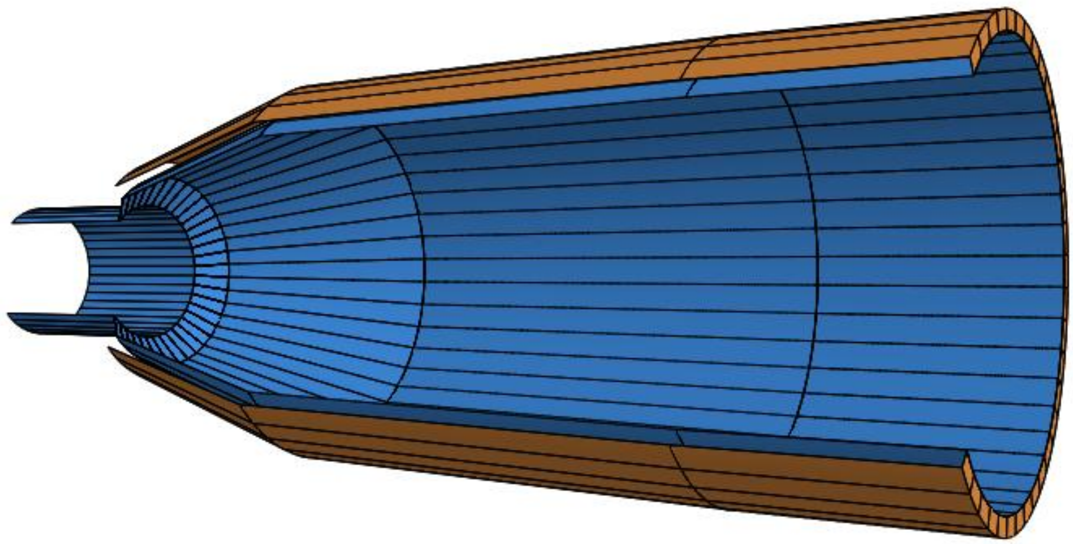

**Figure 7-9.4.56** Chan-Rao Horn designed for 16.5 dB

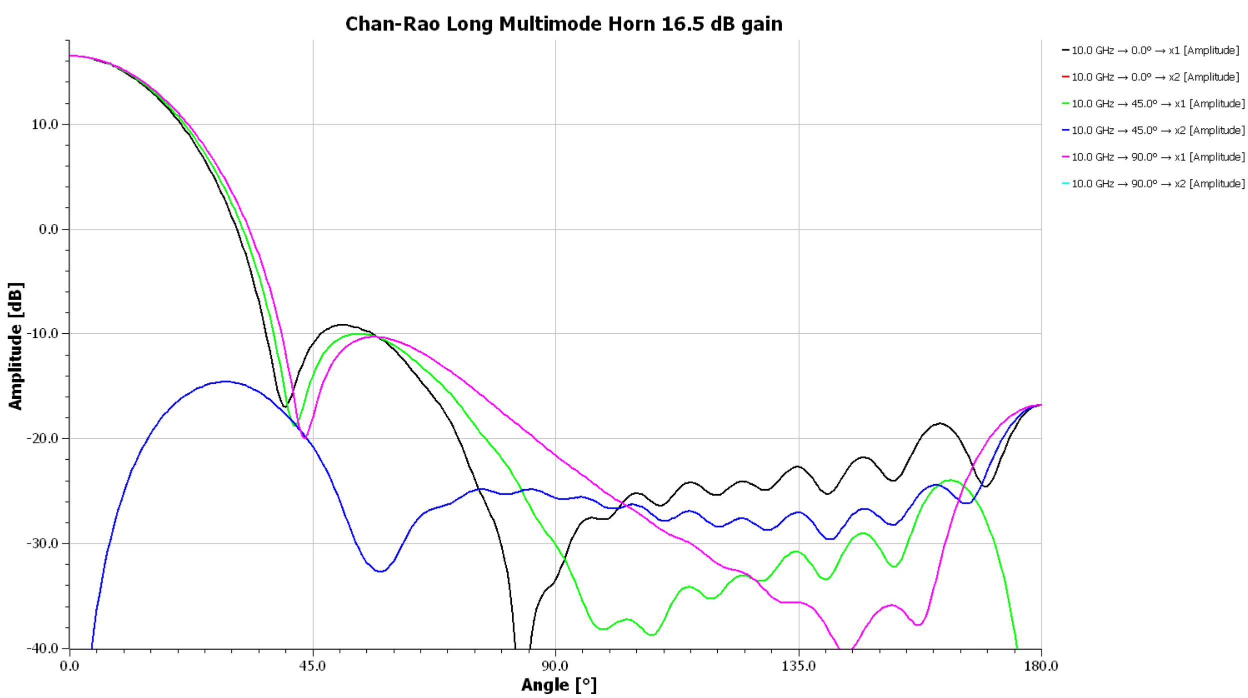


**Figure 7-9.4.57** Center frequency pattern of Chan-Rao Horn designed for 16.5 dB gain

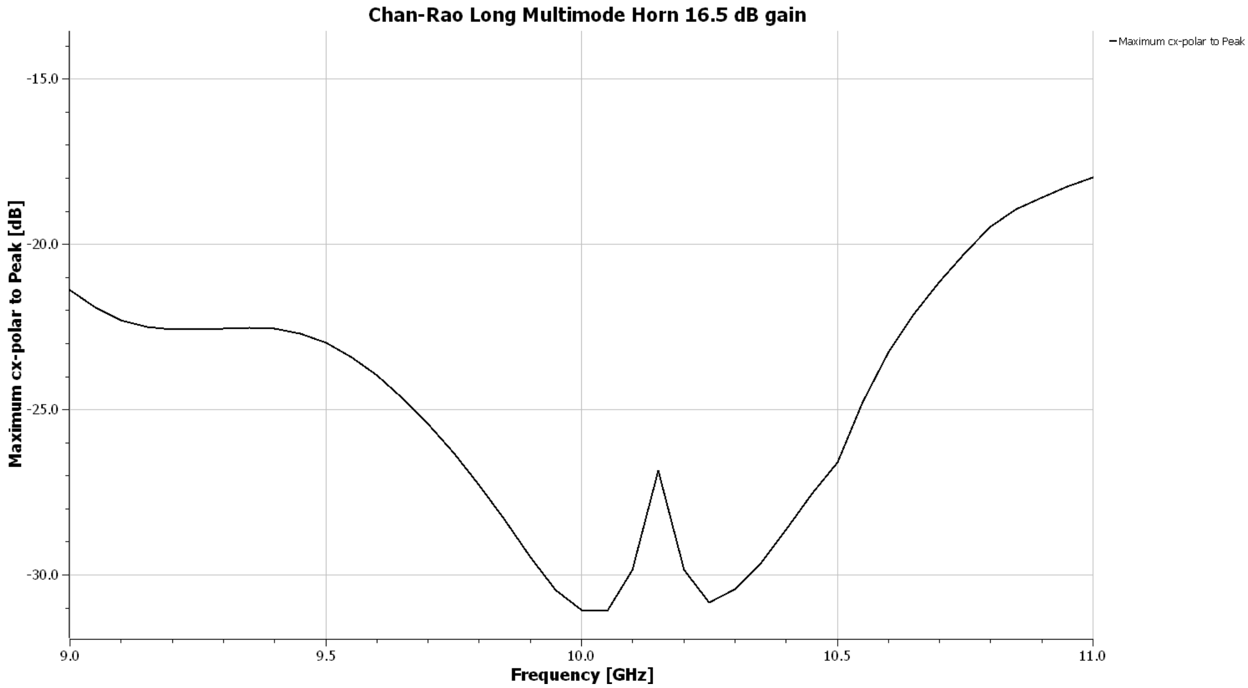


**Figure 7-9.4.58** Cross polarization response of Chan-Rao Horn designed for 16.5 dB gain

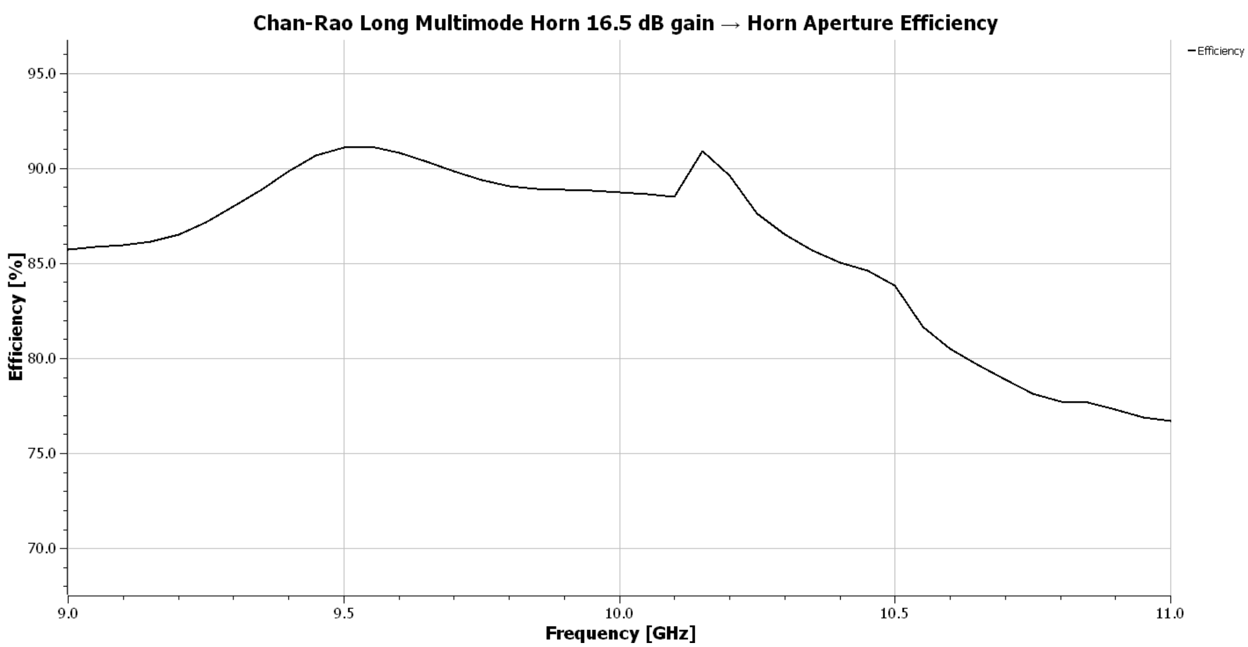


**Figure 7-9.4.59** Aperture efficiency of Chan-Rao Horn designed for 16.5 dB gain

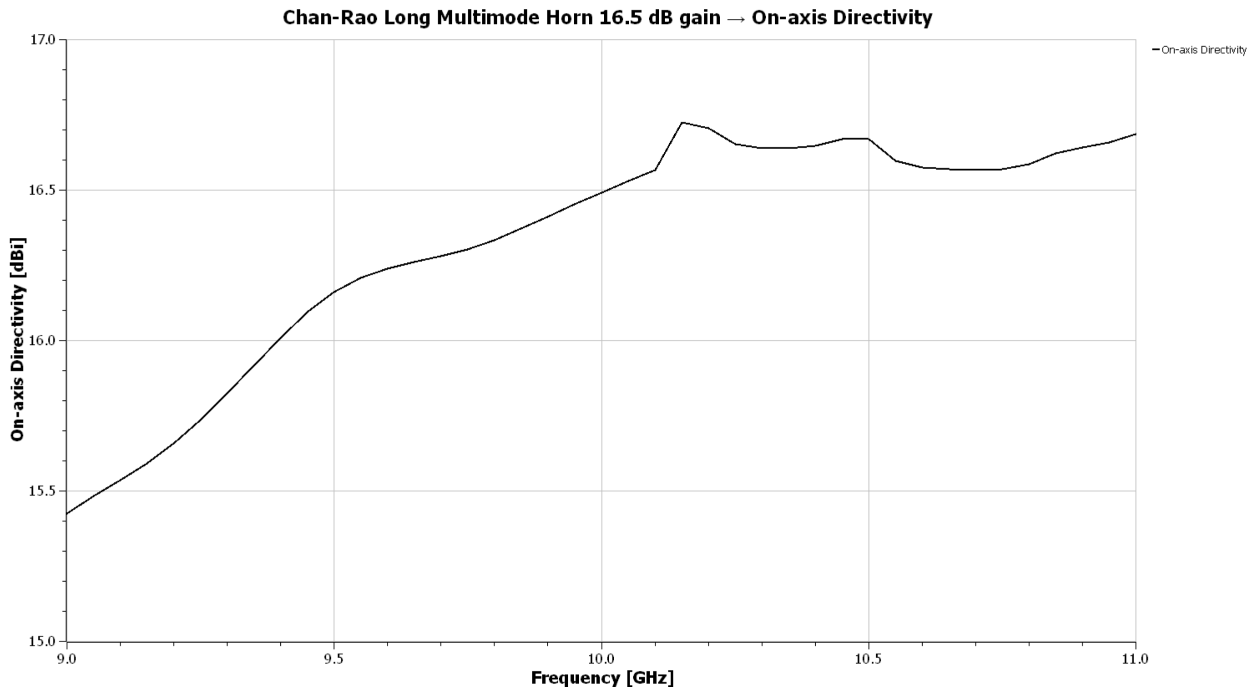


**Figure 7-9.4.60** On-axis Directivity of Chan-Rao Horn designed for 16.5 dB gain

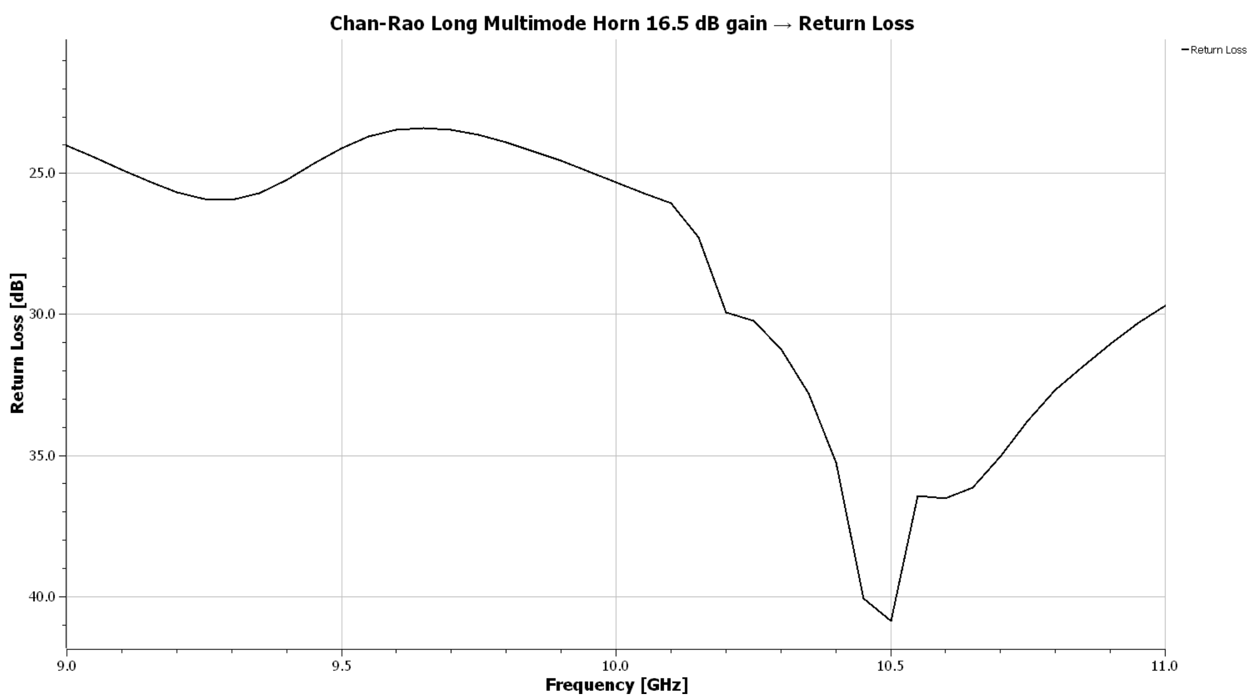


**Figure 7-9.4.61** Return Loss of Chan-Rao Horn designed for 16.5 dB gain

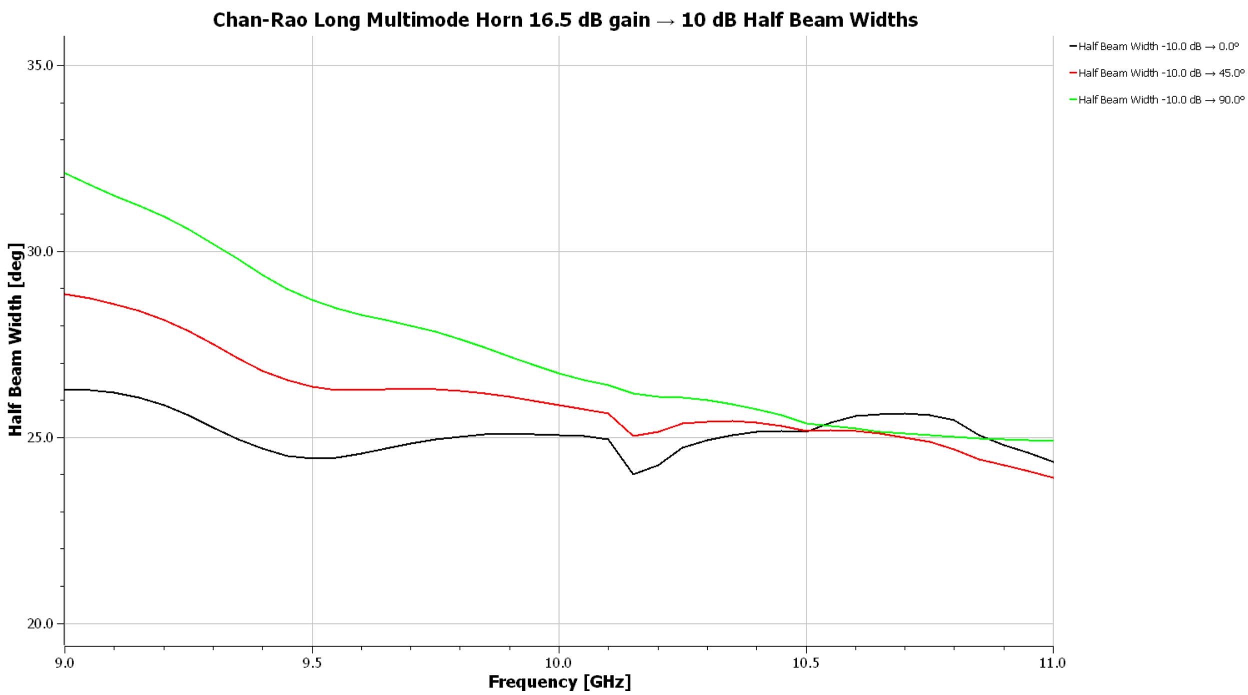


**Figure 7-9.4.62** 10 dB Half Beamwidth of Chan-Rao Horn designed for 16.5 dB gain

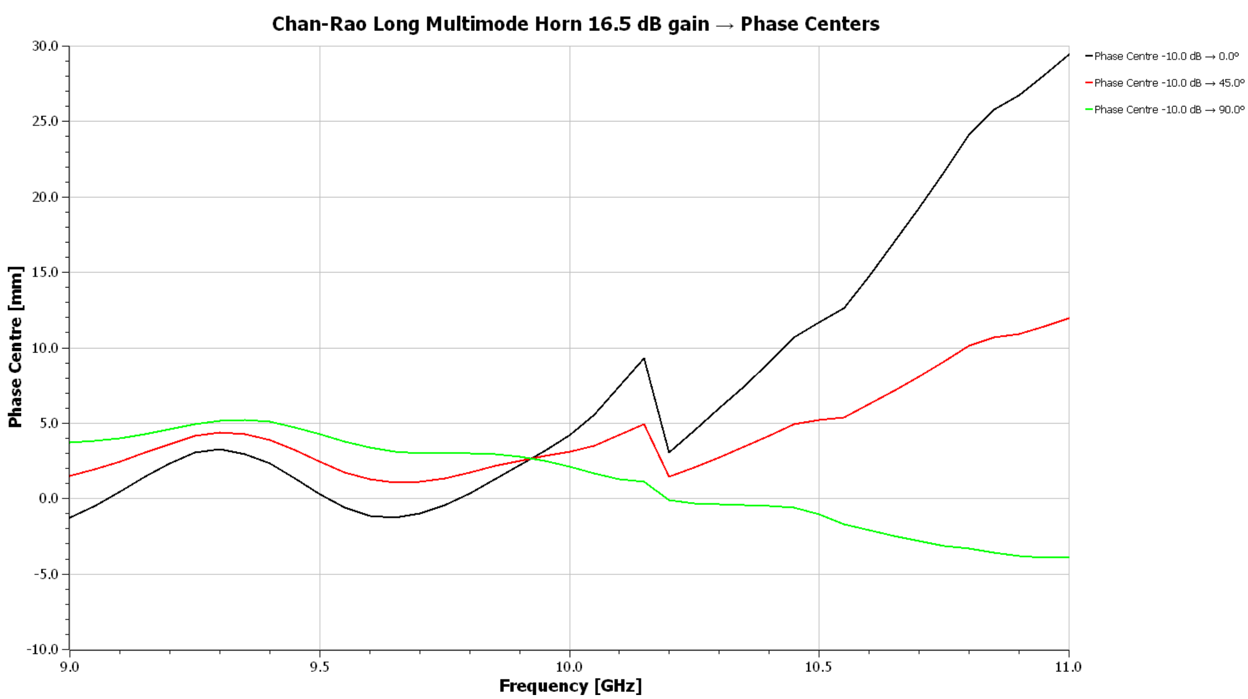


**Figure 7-9.4.63** 10 dB Phase Center of Chan-Rao Horn designed for 16.5 dB gain

## 20 dB Gain Chan-Rao High Aperture Efficiency Horn w/ Long Bell

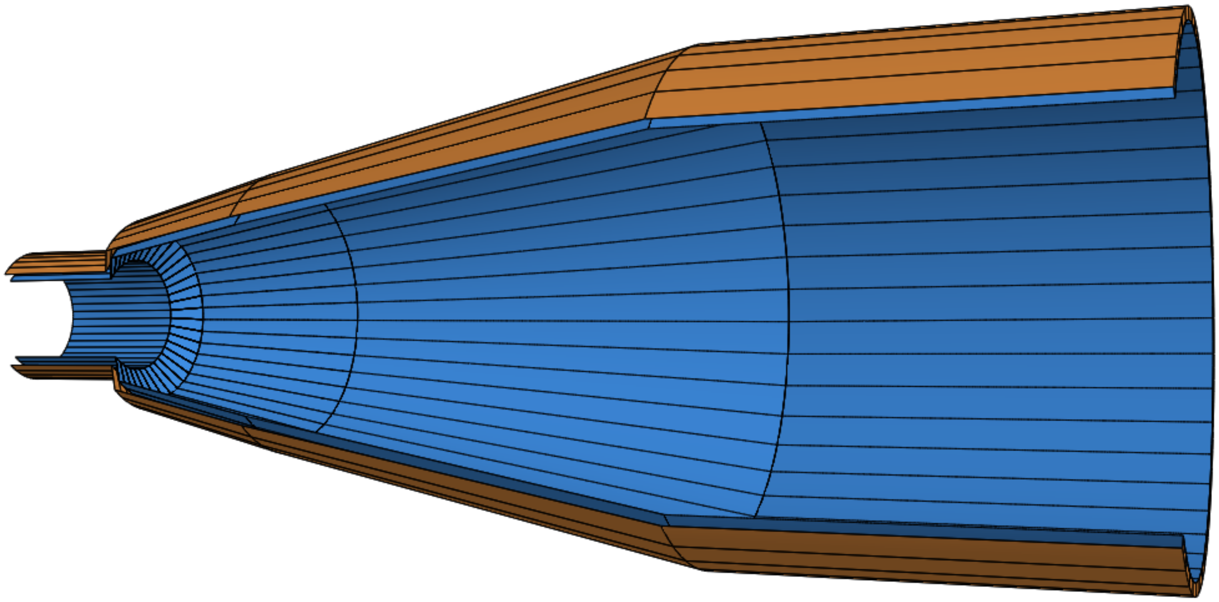

**Figure 7-9.4.64** Chan-Rao Horn designed for 20 dB

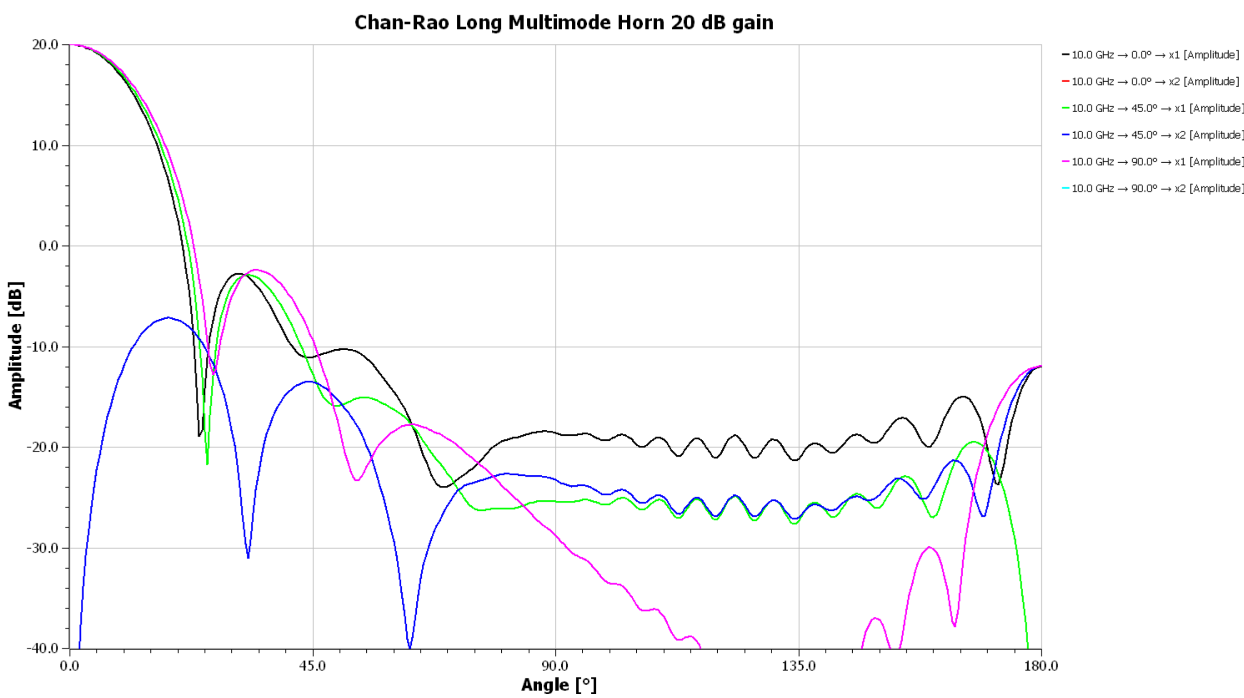


**Figure 7-9.4.65** Center frequency pattern of Chan-Rao Horn designed for 20 dB gain

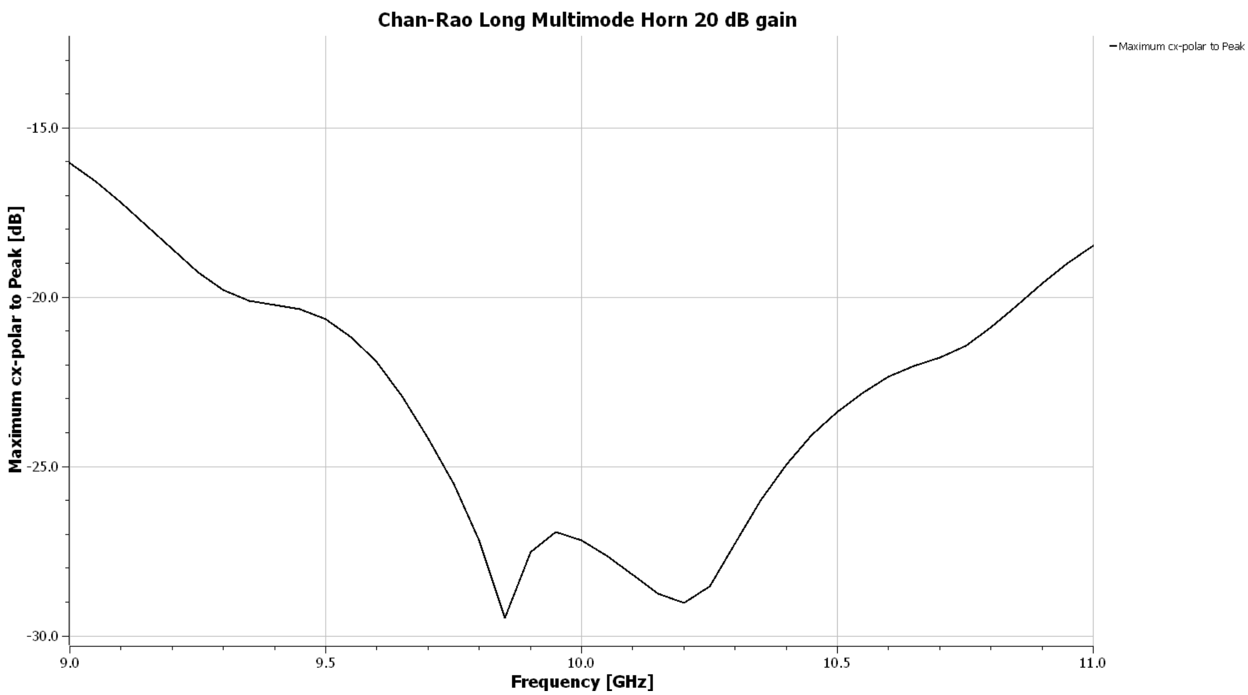


**Figure 7-9.4.66** Cross polarization response of Chan-Rao Horn designed for 20 dB gain

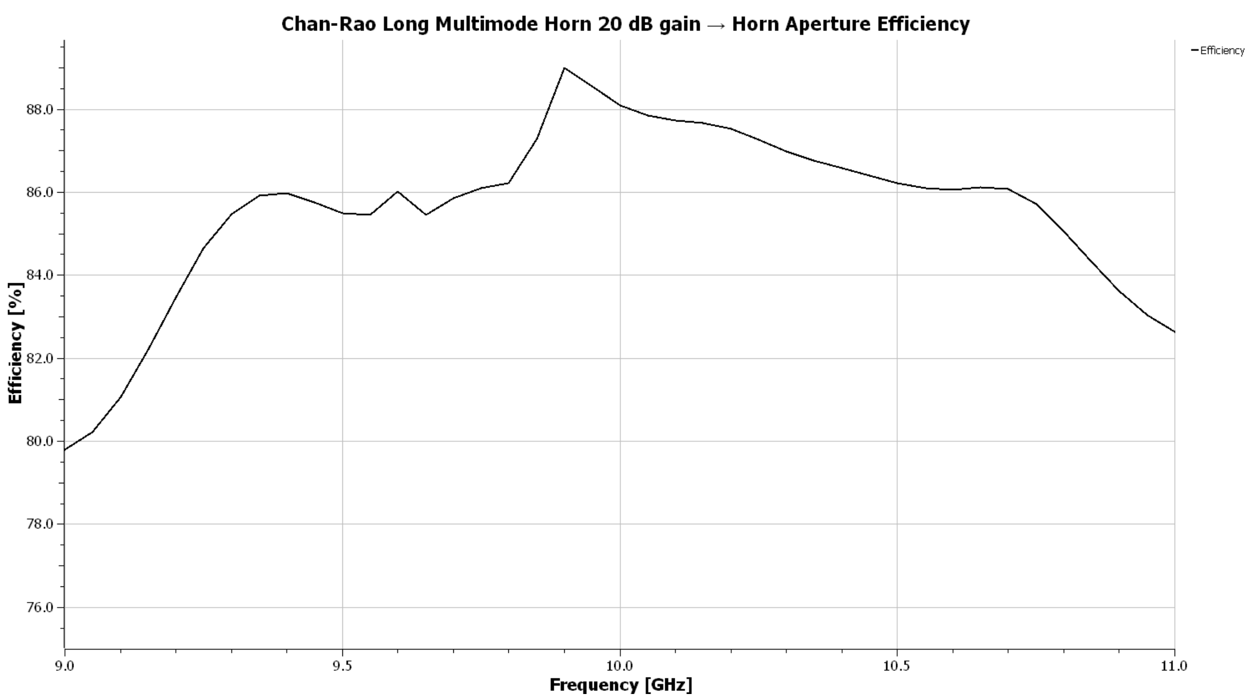


**Figure 7-9.4.67** Aperture efficiency of Chan-Rao Horn designed for 20 dB gain

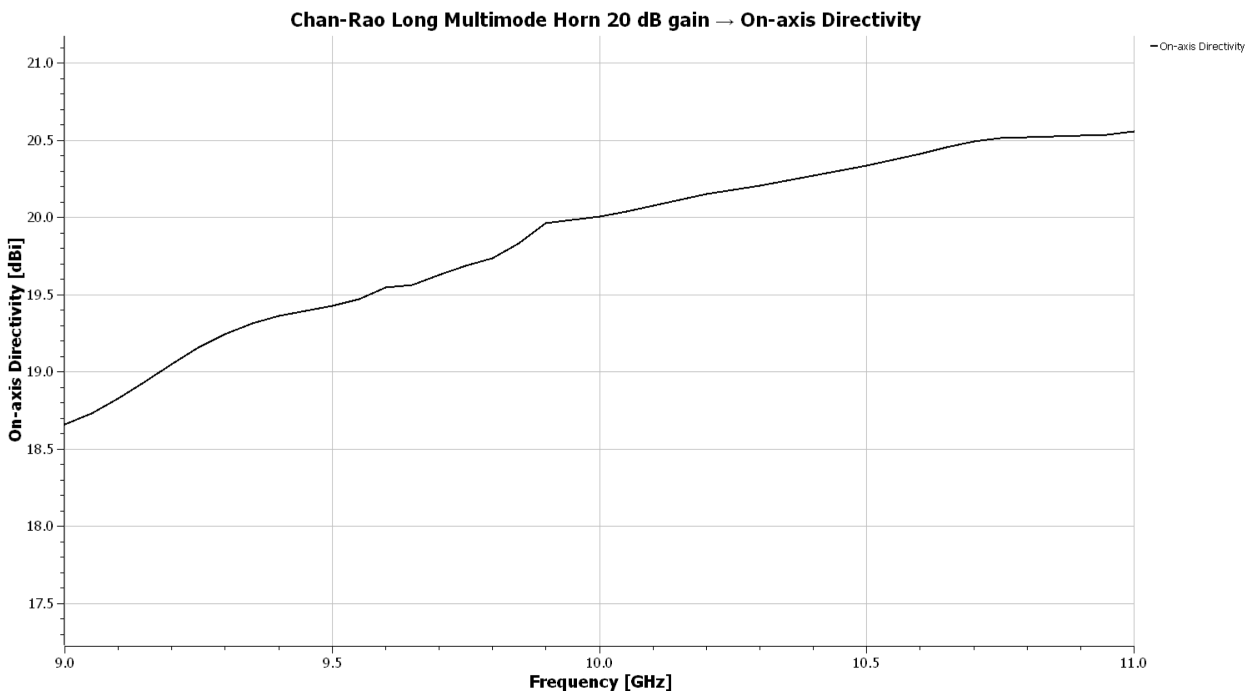


**Figure 7-9.4.68** On-axis Directivity of Chan-Rao Horn designed for 20 dB gain

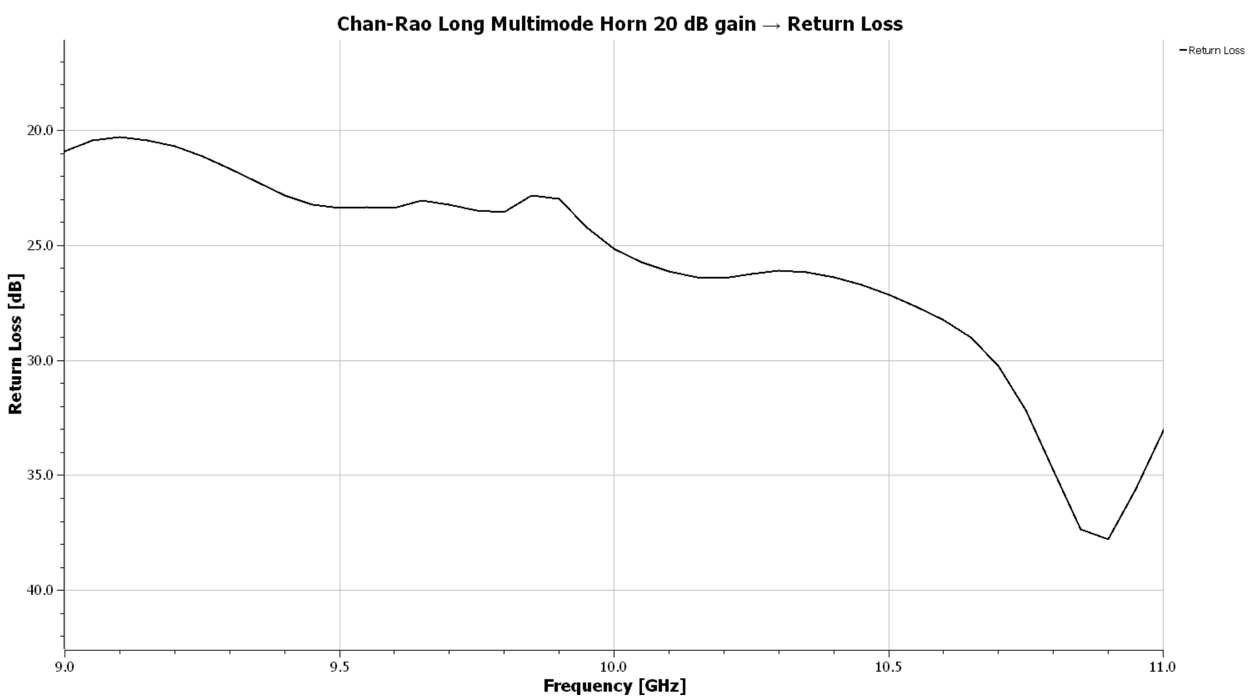


**Figure 7-9.4.69** Return Loss of Chan-Rao Horn designed for 20 dB gain

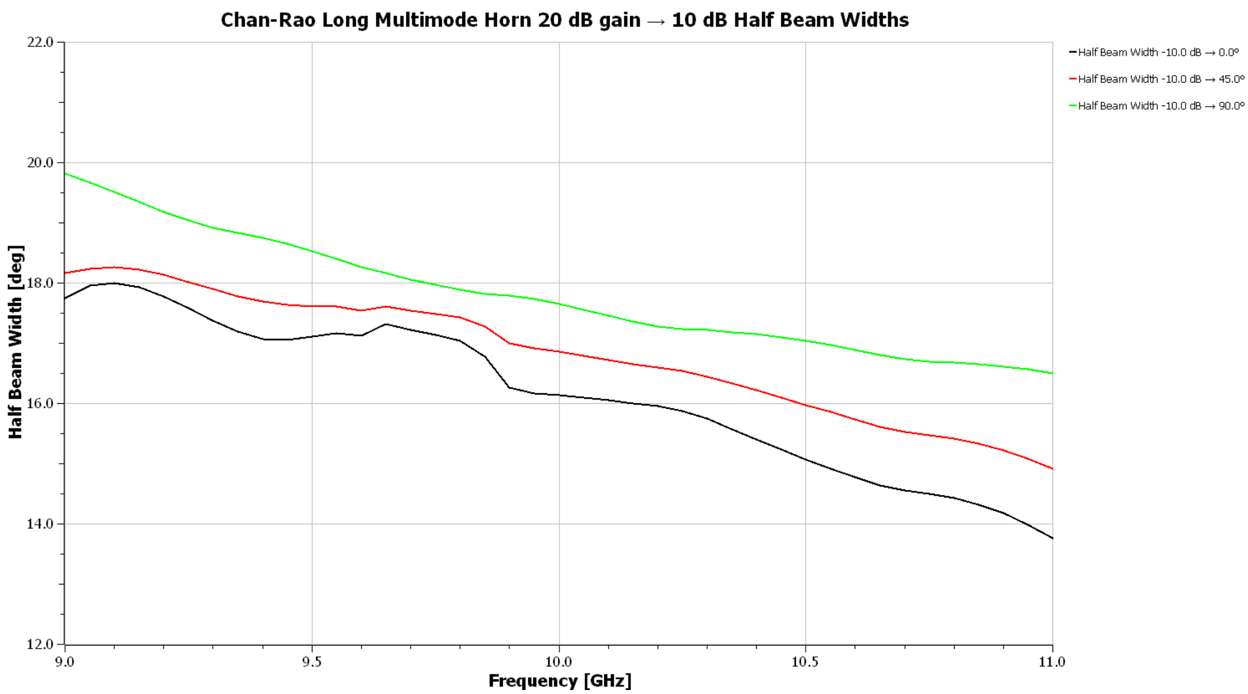


**Figure 7-9.4.70** 10 dB Half Beamwidth of Chan-Rao Horn designed for 20 dB gain

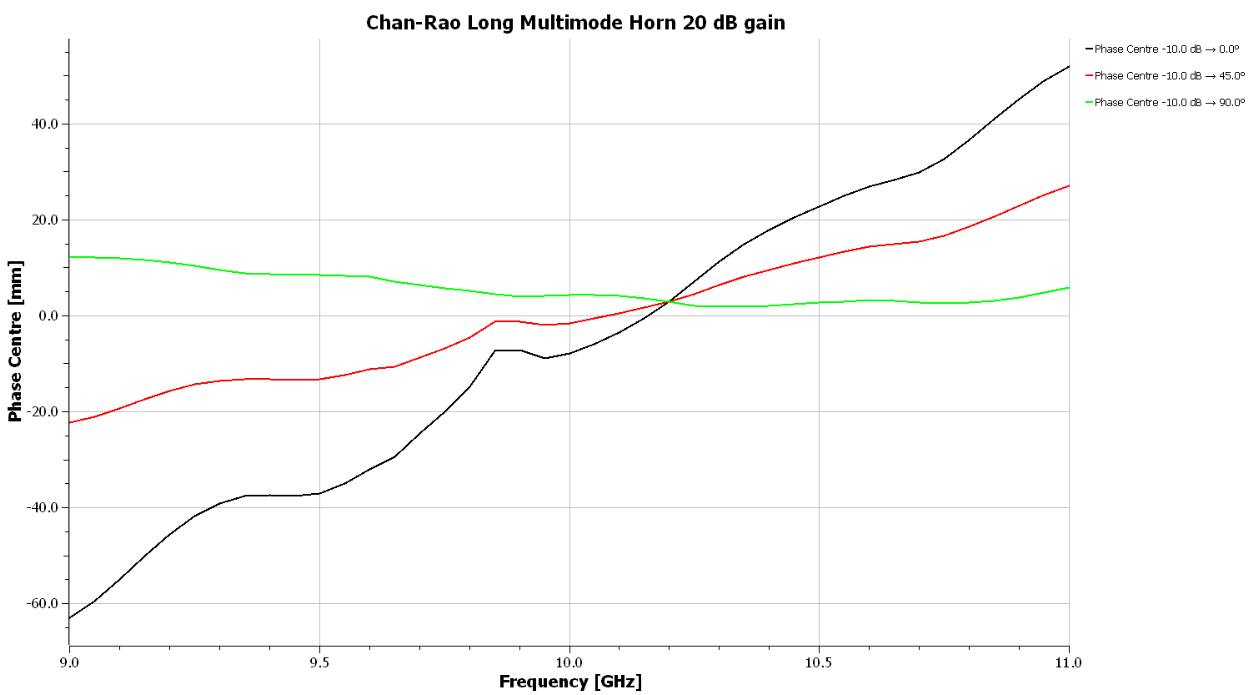


**Figure 7-9.4.71** 10 dB Phase Center of Chan-Rao Horn designed for 20 dB gain

## 24 dB Gain Chan-Rao High Aperture Efficiency Horn w/ Long Bell

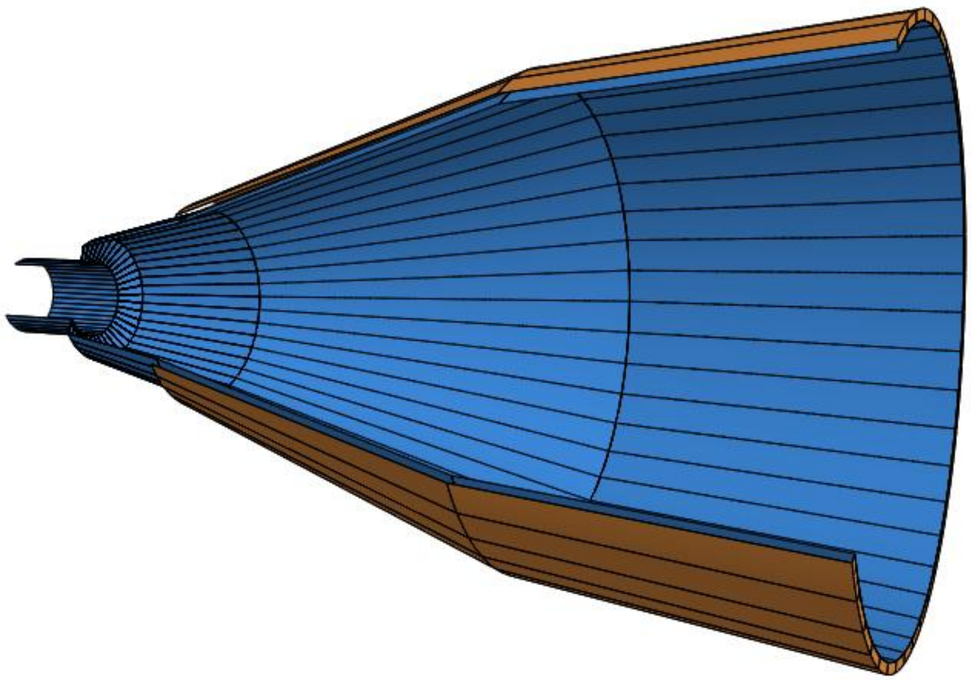

**Figure 7-9.4.72** Chan-Rao Horn designed for 24 dB

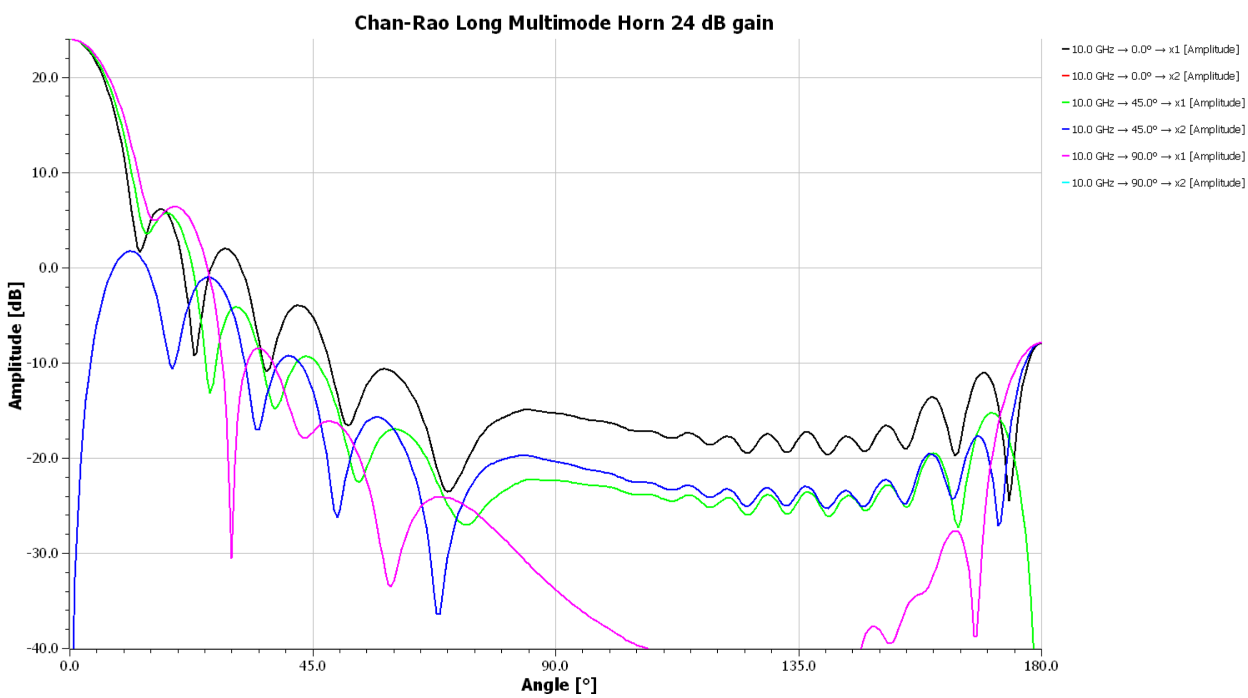


**Figure 7-9.4.73** Center frequency pattern of Chan-Rao Horn designed for 24 dB gain

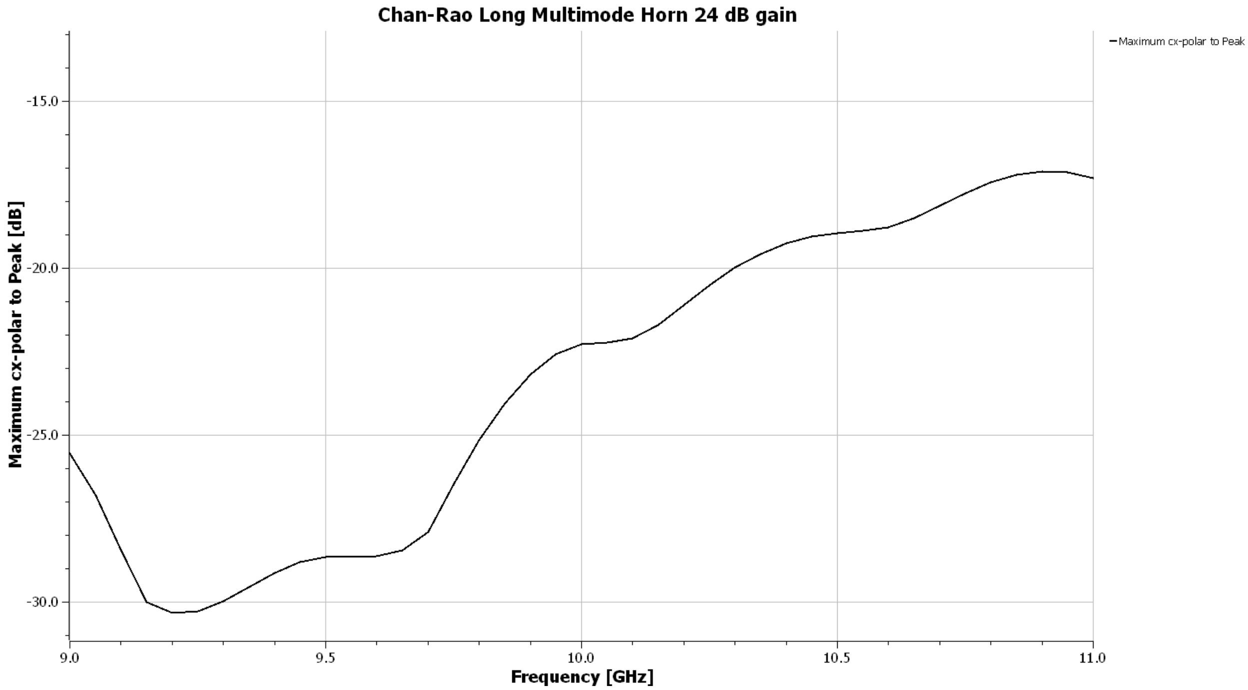


**Figure 7-9.4.74** Cross polarization response of Chan-Rao Horn designed for 24 dB gain

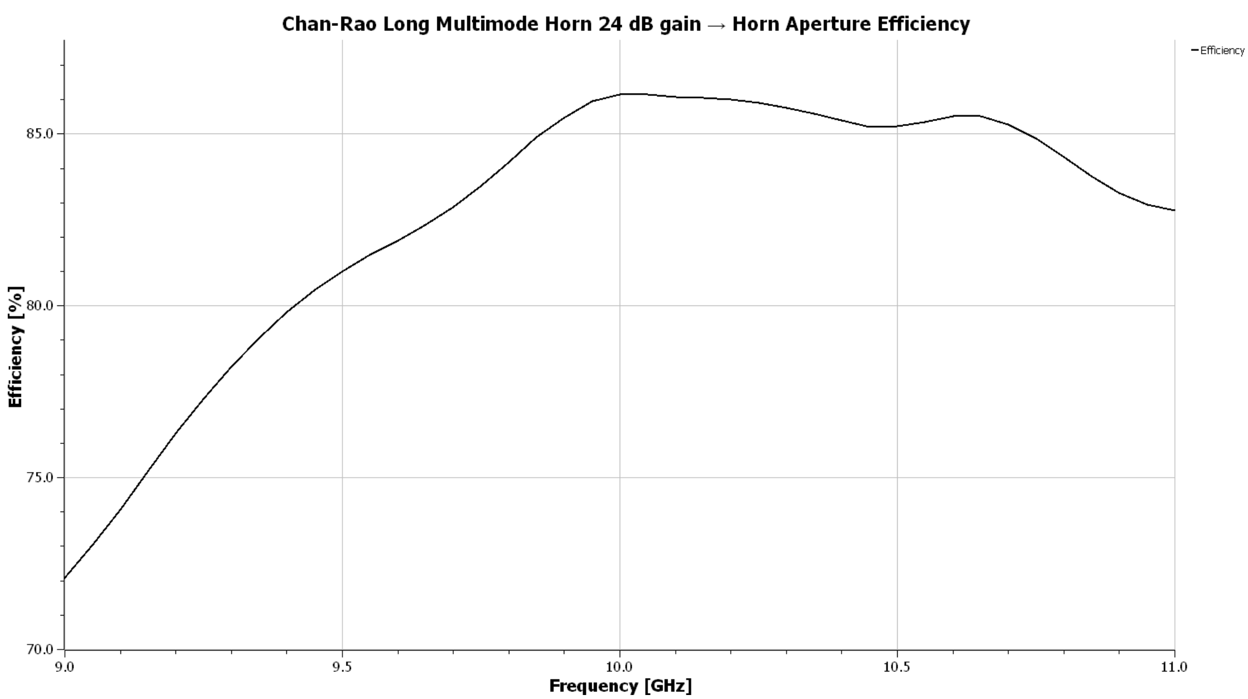


**Figure 7-9.4.75** Aperture efficiency of Chan-Rao Horn designed for 24 dB gain

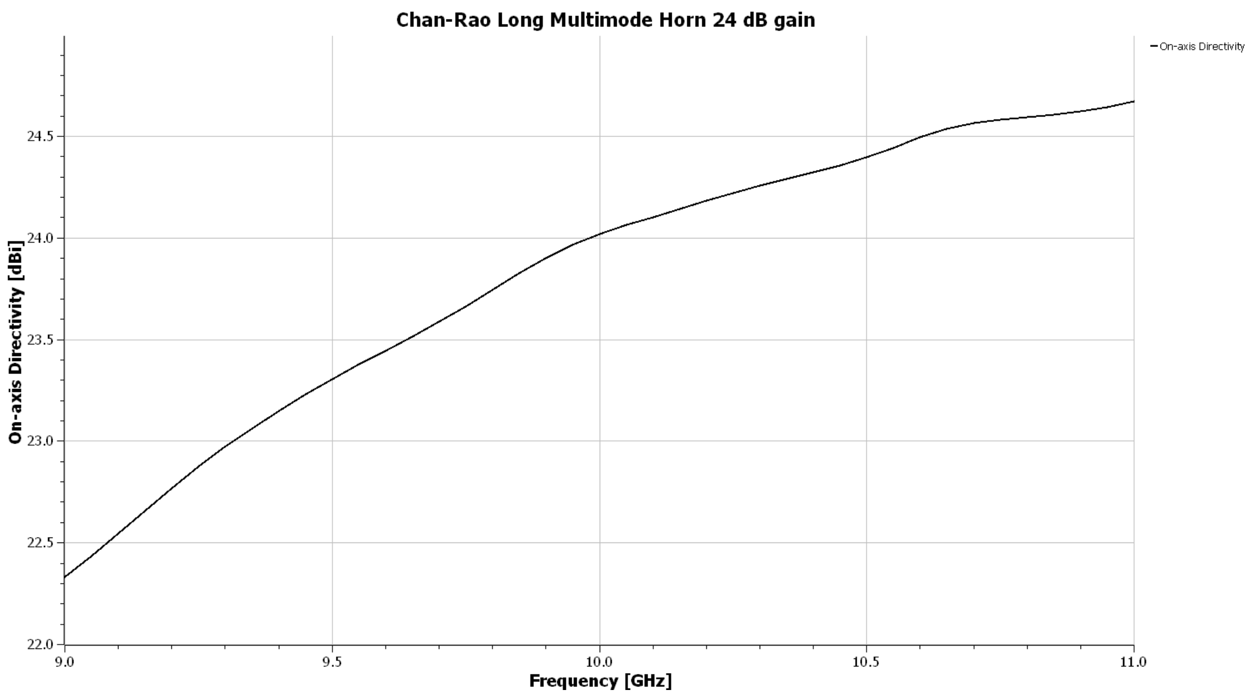


**Figure 7-9.4.76** On-axis Directivity of Chan-Rao Horn designed for 24 dB gain

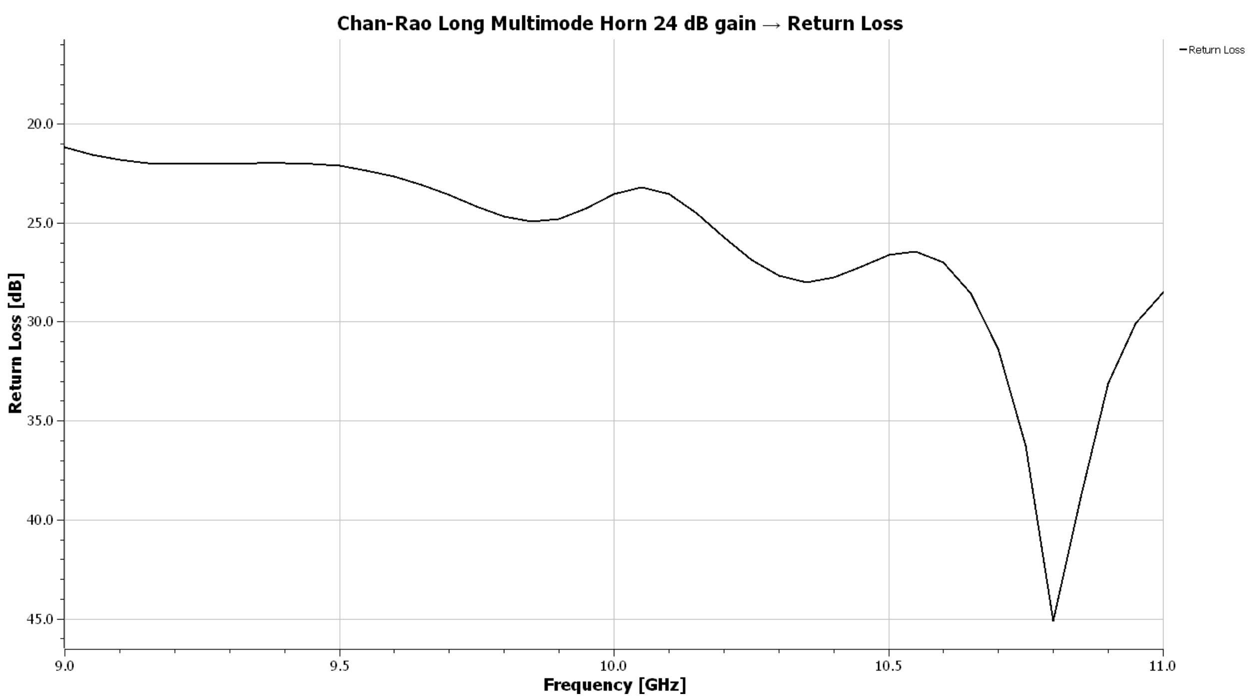


**Figure 7-9.4.77** Return Loss of Chan-Rao Horn designed for 24 dB gain

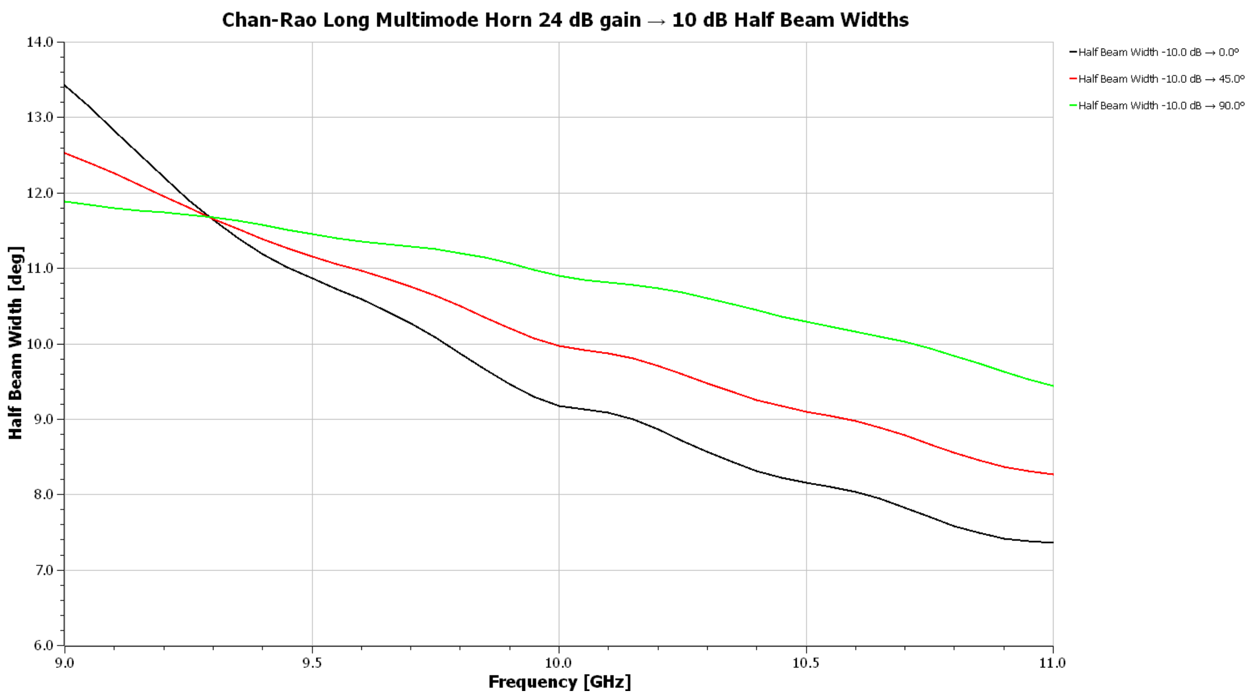


**Figure 7-9.4.78** 10 dB Half Beamwidth of Chan-Rao Horn designed for 24 dB gain

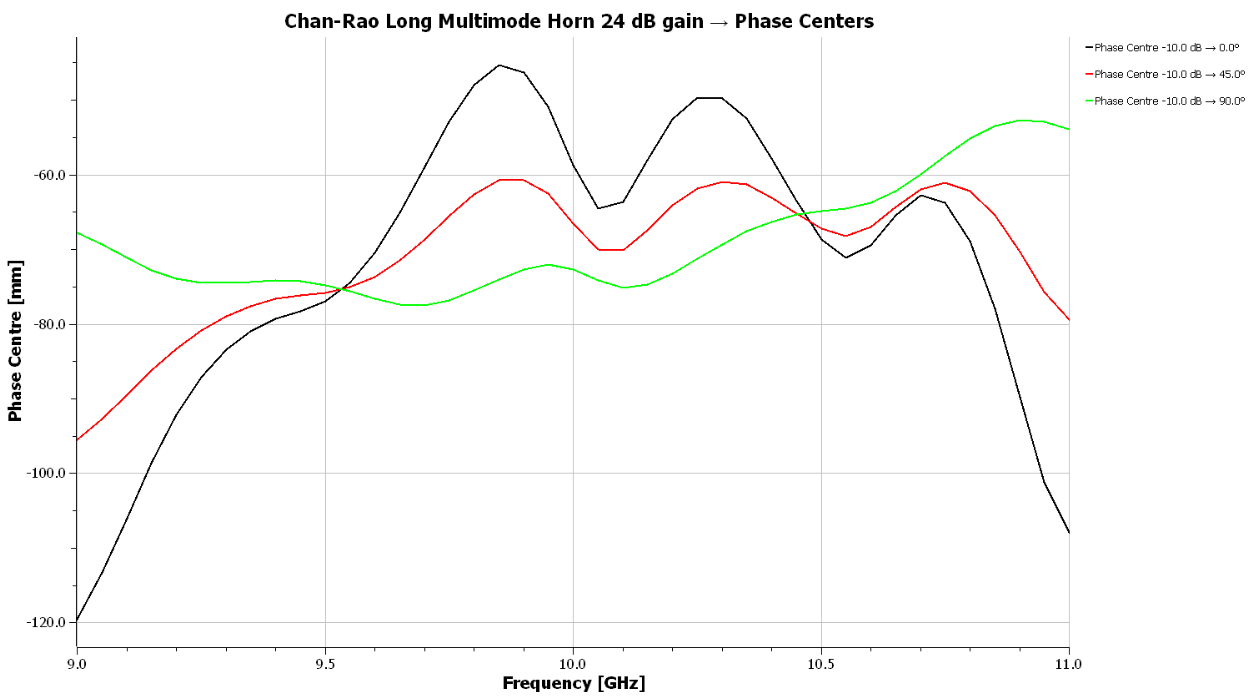


**Figure 7-9.4.79** 10 dB Phase Center of Chan-Rao Horn designed for 24 dB gain

[1] Bhattacharyya, A. K., and G. Goyette, “A Novel Horn Radiator with High Aperture Efficiency and Low Cross-polarization and Application in Arrays and Multibeam Reflector Antennas,” *IEEE Trans. on Antennas and Propagation,* Vol. AP-52, No. 11, November 2004, pp. 2850-2859.

[2] Bhattacharyya, A. K., and G. Goyette, Chapter 4 Smooth Wall Multimode Horns for High Aperture Efficiency – Theory, Design, and Applications, *Handbook of Reflector Antennas and Feed Systems, vol. II,* Artech, Boston, 2013.

[3] Chan, K. K., and S. K. Rao, “Design of High Efficiency Circular Horn Feeds for Multibeam Reflector Applications,” *IEEE Trans. on Antennas and Propagation,* Vol. AP-56, No. 1, January 2008, pp. 253-258.