Chapter 3

Multi-frequency Ortho-mode Transducer

The analysis in Chapter 2 shows that the higher-order modes get coupled in an oversized circular waveguide having a discontinuity. This chapter deals with multiple discontinuities in the form of circular waveguide junctions having coaxial probes for coupling at different frequency bands. The design, modal analysis and measured results of a new type of ortho-mode transducer are presented. In this device, cascaded circular waveguides excited by rectangular waveguides through co-axial line fed probes are used. Mechanisms of cascading of waveguides, excitation of cascaded circular waveguides and transitions have been investigated in order to achieve the intended performance at widely separated frequency bands. A four frequency Orthomode Transducer (OMT) at 6.6, 10.65, 18 and 21 GHz has been designed and developed. This concept has been utilized also to develop a three frequency mode transducer at 18.7, 23.8 and 36.5 GHz. The simulated results are compared with measured results. These transducers may find wide applications in the feed systems for reflector type of antenna for scanning microwave radiometer sensors.

3.1 Design and Analysis

The design complexity of mode transducers working at multiple frequency bands increases due to the presence of multiple discontinuities (symmetrical and asymmetrical) in the path of propagating signals at different frequency bands. A suitable method to design such transducers would be to cascade the mode transducers at individual frequency bands such that the cross-sectional dimensions at higher frequency bands are at cutoff for the lower frequency bands (see Figure 2.1). But, the waveguide sections at lower frequency bands (supporting only the dominant mode) become over-sized at higher frequencies and support higher-order modes, which are excited because of structural discontinuities. If orthogonal polarizations are required at individual frequency band, then polarization matched power sensing mechanisms have to be used in the cascaded sections. In this case, the higher frequency dominant mode signal gets coupled to the lower frequency power sensing ports.
thereby increasing the insertion loss of the device. In the mode transducers investigated in this chapter, the higher-order modes are generated because of (i) transition in the form of step or tapered discontinuity between two waveguides of different cross-sections and (ii) probe which senses power at lower frequency band acts as a radial discontinuity and coupler for higher frequency signal. Since, the design goal is to ensure dominant mode purity at each frequency band, the higher-order modes have to be suppressed and all the frequency ports have to be decoupled. The dominant mode purity at each frequency band of OMT will ensure the desired radiation patterns of a corrugated horn antenna. Hence, it is worthwhile to estimate the modal amplitude of different higher-order modes generated because of the discontinuities. Finite element method (FEM) based Ansoft’s HFSS software has been used for modeling, analysis, design-optimization and estimation of amplitudes of different higher-order modes. In the OMT design, the frequencies considered are 6.6 GHz, 10.65 GHz, 18 GHz and 21 GHz, which correspond to frequencies of a radiometer. The design steps for the development of four-frequency ortho-mode transducer are explained in the following sections.

3.1.1 Modal Analysis of Waveguide Sections Cascaded with Step Junctions

It is simple to join primary waveguides (main arms) of OMTs at individual frequency bands using step junctions between waveguides as shown in Figure 3.1. But this geometry should be analyzed in terms of higher-order modes. Figure 3.1 shows four straight circular waveguide sections \( A_s, B_s, C_s \) and \( D_s \) joined together to form stepped waveguide transitions. When pure \( TE_{11} \) mode is incident in section-\( A_s, B_s, C_s, D_s \) corresponding to 21, 18, 10.65 and 6.6 GHz respectively, it is of interest to evaluate the modal power in the output waveguide section-\( D_s \) which is oversized for 21, 18 and 10.65 GHz and supports the higher-order modes generated due to step junctions between waveguide pairs \( A_s, B_s \) and \( B_s, C_s, D_s \). The analysis presented in Section 2.3 for single step junction showed that sufficient power couples in the higher-order modes (see Figure 2.23), if the output waveguide section is over-sized. Here, simulation has been done for four cascaded step junctions (see Figure 3.1) to find out the modal power of the desired dominant mode (\( TE_{11} \) mode) and the undesired higher-order modes in the output waveguide section \( D_s \).
For the 3-D model of the step junctions used in HFSS, the diameters of sections A_s, B_s, C_s and D_s are chosen as 9.4, 11, 19 and 32.54 mm for the propagation of dominant TE_{11} mode at 21, 18, 10.65 and 6.6 GHz respectively. The lengths of the individual sections have been selected as 34, 53, 54 and 78 mm respectively. The higher-order propagating modes supported at the waveguide section-D_s that feeds a corrugated horn are TM_{01}, TE_{21}, TE_{01}, TM_{11}, TE_{31}, TM_{21}, TE_{41}, TE_{12}, TM_{02}, TM_{31} at 18 GHz. Along with these modes, additional propagating higher-order modes at 21 GHz are TE_{51}, TE_{22}, TE_{02}, TM_{12}. At 10.65 GHz, TM_{01} and TE_{21} are the higher-order propagating modes in section-D_s.

From the modal analysis results it is found that the dominant mode purity is not achievable in the section D_s (Figure 3.1) and almost half of the power gets coupled to higher-order modes (TM_{11} and TE_{12}) at 18 and 21 GHz. Additionally, step discontinuity also causes reflection of the input power. The modal amplitudes (in dB) of different modes at the output of 6.6 GHz section for the geometry of Figure 3.1, have been computed at all the four frequency bands. It is found that for the incident TE_{11} mode in the section-D_s and C_s at 6.6 and 10.65 GHz respectively, there is no power coupling in the higher-order modes but there is a reflection of 3.6% power at 10.65 GHz in the waveguide section-C_s. At 18 GHz, for the incident TE_{11} mode in the section-B_s, 11.4% power is coupled to TE_{12} mode, 33.04% power is coupled to TM_{11} mode, power in the desired TE_{11} mode is only 53.19% in section-D_s and 10.48 % power is reflected in section-B_s. Similar behavior was observed at 21 GHz. These results show that the step discontinuity in cascaded circular waveguides couples power mainly in the higher-order TE_{ln} (n>1)and TM_{ln} (n≥1) modes at 10, 18 and 21 GHz. Thus, the modal analysis shows that waveguide sections cascaded with the step junctions not only couple sufficient power in the higher-order modes at higher frequencies, but they also reflect the incident power since they act as sharp discontinuity. Sharp
discontinuities should be changed into gradual tapers in order to minimize losses due to reflection and higher-order mode coupling.

A common aperture conical corrugated horn (with $15^\circ$ flare angle, 40 mm length and 16 number of corrugations) when excited with pure $\text{TE}_{11}$ mode at its input, offered optimum performance at all the four frequency bands. With pure $\text{TE}_{11}$ mode excitation, the horn resulted into cross-polar radiation level better than 27 dB at 18 and 21 GHz. Similar, performance was observed at 10.65 and 6.6 GHz. But, if this horn is excited by the mode transducer of Figure 3.1, the computed radiation patterns become asymmetric in the azimuth planes and cross-polar radiation level also deteriorates to -13.5 dB at 18 and 21 GHz as compared to -27 dB with pure $\text{TE}_{11}$ mode excitation. This was due to higher-order mode coupling at these frequencies. The analysis presented in Section 2.3 for symmetrical discontinuity in the form of waveguide sections joined with tapered section showed that maximum power couples in the dominant $\text{TE}_{11}$ mode, if the taper angle is less than 10 degrees (see Figure 2.23). Therefore, in order to minimize reflected power and the power coupled to higher-order modes at higher frequencies, the step junctions have to be replaced by gradual tapered junctions. The next section deals with design and modal analysis of different waveguide sections joined by tapered sections.

### 3.1.2 Waveguide Sections Cascaded with Tapered Sections

Figure 3.2 shows four circular waveguide sections $A_t$, $B_t$, $C_t$ and $D_t$ joined together by a tapered section between two successive waveguide sections. The dimensions of the straight waveguide sections are same as mentioned in previous section for Figure 3.1.

![Figure 3.2 Circular waveguide sections $A_t$, $B_t$, $C_t$ and $D_t$ cascaded with tapered sections.](image-url)
The taper angle and length of the tapered sections between waveguide sections \( A_t, B_t(\theta_1, A_1), B_t, C_t(\theta_2, A_2) \) and \( B_t, C_t(\theta_3, A_3) \) have to be optimized in order to minimize the power in the higher-order modes and maximize the power in the desired dominant \( \text{TE}_{11} \) mode. Taking some initial taper angle and length of the tapered section between two successive waveguide sections, a 3-D model of the structure (Figure 3.2) was modeled using Ansoft HFSS. The taper angles and taper lengths were optimized to minimize power in higher-order modes in the section \( D_t \). The optimum flare angles for the geometry (Figure 3.2) have been found to be between 3 to 6 degrees to confine power in \( \text{TE}_{11} \) mode. The optimized design dimensions of the waveguide sections at different frequencies are presented in Table 3.1.

**Table 3.1** The design dimensions of the waveguide sections at different frequencies.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Wavelength (mm)</th>
<th>Cut off Diameter for ( \text{TE}_{11} ) mode in CWG* (mm)</th>
<th>Selected Diameter of CWG (mm)</th>
<th>Flare Angles of the Tapered Section (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.60</td>
<td>45.45</td>
<td>26.64</td>
<td>32.54</td>
<td>5.68</td>
</tr>
<tr>
<td>10.65</td>
<td>28.17</td>
<td>16.51</td>
<td>19.00</td>
<td>4.97</td>
</tr>
<tr>
<td>18.00</td>
<td>16.67</td>
<td>9.77</td>
<td>11.00</td>
<td>2.86</td>
</tr>
<tr>
<td>21.00</td>
<td>14.29</td>
<td>8.37</td>
<td>9.40</td>
<td>90.0 (perfect short)</td>
</tr>
</tbody>
</table>

* CWG stands for circular waveguide

The modal power was computed at 21 GHz at the output waveguide section (\( D_t \)) having the largest cross-sectional dimension considering a unity power incident at the input waveguide sections at each frequency. It is found that for optimum flare angles, the power coupling in higher-order modes is negligible and 99% (0.044 dB) power is confined in the desired \( \text{TE}_{11} \) mode in the waveguide section \( D_t \). The power in the dominant \( \text{TE}_{11} \) mode at 18 GHz is of the same order and it is better at 10.65 and 6.6 GHz for the optimized transition. The reflected power is less than 0.7% (-21.6 dB) at all the frequencies. This configuration (Figure 3.2) avoids the power conversion into higher-order modes due to discontinuity between two circular waveguides (i.e., for symmetrical discontinuity) and its also does not deteriorate the return loss in the axial direction. Therefore, this configuration (Figure 3.2) with tapered section can be used for the design of cascaded orthomode transducers at four frequency bands.
The radiation patterns of the corrugated horn (described in Section 3.1.1) excited with the mode transducer geometry of Figure 3.2 was computed at 18 GHz and 21 GHz. The computed radiation patterns showed symmetrical patterns and cross polar radiation better than -27 dB, cross-polar level and pattern symmetry at 6.6 and 10.65 GHz were same as that of the horn excited with pure TE_{11} mode. Thus, the desired radiation performance of a corrugated horn can be achieved at each frequency band, if the horn is fed by waveguide sections joined with tapered sections ensuring TE_{11} mode purity.

### 3.1.3 Effects of Co-axial Probes

For exciting TE_{11} mode in the circular waveguide sections, coaxial probes have been used. Since, a common aperture OMT is to be used for all the frequency bands to excite the horn antenna, the waveguide sections for individual frequency bands cannot be short terminated for maximum power coupling. As shown in Figures 3.3, the waveguide section for 6.6 GHz frequency band is terminated by waveguide section (C_t) at 10.65 GHz through a tapered transition which is at cut-off for 6.6 GHz. Similarly, 18 GHz section (B_t) is at cut-off for 10.65 GHz and 21 GHz section (A_t) is at cut-off for 18 GHz. In this configuration, the location of the probe from the cut-off region which is in the form of tapered transition can be optimized for a particular depth of the probe for maximum power coupling to the primary circular waveguide.

Presently three probes are taken in waveguides at 6.6, 0.65 and 18 GHz for higher-order mode analysis at 21 GHz. The probe depths and locations for coupling maximum power in the circular waveguide have been computed using the expressions given in [28] and described in Appendix A.1 and A.2. The earlier works have been done on the mutual impedance between probes in a circular waveguide [79], [80] supporting only the dominant mode. The higher-mode analysis treating multiple probes as discontinuity in cascaded circular waveguides has not been investigated earlier. Presently, modal analysis using Ansoft HFSS is carried out at 21 GHz in the presence of coaxial probes in 6.6, 10.65 and 18 GHz waveguide sections to compute power coupled to the higher-order modes in the output section D_o for the geometry of Figure 3.3. As analyzed in Chapter 2, probe or post discontinuities couple power in the higher-order TE_{0n}, TM_{0n}, (n\geq1) and TE_{n1}, TM_{n1} (n>1) modes.

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Figure 3.3 Waveguide sections excited with coaxial probe at different frequencies.

The results of higher-order mode analysis for multiple probe discontinuities (Figure 3.3) is shown in Table 3.2 for all the frequencies. Power coupled to successive lower frequency probes is also given in the Table 3.2.

Table 3.2 The power (dB) in dominant and higher-order modes in section-D<sub>T</sub> for tapered junction.

<table>
<thead>
<tr>
<th>Input signal Frequency (GHz)</th>
<th>Higher-order modes</th>
<th>TE&lt;sub&gt;11&lt;/sub&gt; Mode</th>
<th>21 GHz port</th>
<th>18 GHz port</th>
<th>10.65 GHz port</th>
<th>6.6 GHz port</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.0</td>
<td>-8.55</td>
<td>-4.37</td>
<td>-22.0</td>
<td>-4.12</td>
<td>-18.2</td>
<td></td>
</tr>
<tr>
<td>10.65</td>
<td>-12.35</td>
<td>-1.36</td>
<td>&lt;-99</td>
<td>&lt;-99</td>
<td>-7.29</td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td>&lt;=-40</td>
<td>-0.002</td>
<td>&lt;-99</td>
<td>&lt;-99</td>
<td>&lt;-99</td>
<td></td>
</tr>
</tbody>
</table>

It was found that for the incident TE<sub>11</sub> mode in the waveguide section (A<sub>t</sub>) at 21 GHz, 11.07% power gets coupled to higher-order modes, 52.17% power (i.e., -2.83 dB) couples to 18 GHz coaxial probe, 2.69% couples to 10.65 GHz coaxial probe, 0.26% couples to the 6.6 GHz coaxial probe, 6.67% power is reflected by probes and the power in the required TE<sub>11</sub> mode is only 24.59% (i.e., -6.09 dB). The modal analysis was also carried out at 18 GHz in the presence of coaxial probes in 6.6 and 10.65 GHz waveguide sections.

It was found that for the incident TE<sub>11</sub> mode in the waveguide section (B<sub>t</sub>) at 18 GHz, 14% power couples to the higher-order modes, 38.73% couples to 10.65 GHz coaxial probe, 1.53% couples to the 6.6 GHz coaxial probe, 9.53% power is reflected by probes and the
power in the required $\text{TE}_{11}$ mode is only 36.56%. Thus, at higher frequencies the power is couples to higher-order modes and also to the lower frequency ports, which effectively reduces the power in the desired $\text{TE}_{11}$ mode.

At 10.65 GHz, for $\text{TE}_{11}$ mode incident in the section ($C_1$), 5.82% gets coupled to $\text{TM}_{01}$ mode, 18.66% gets coupled to 6.6 GHz probe, 2% gets reflected from the probe at 6.6 GHz and 73.2% remains in the required $\text{TE}_{11}$ mode. Thus, this modal analysis shows that at higher frequency bands, the power incident from the dominant mode waveguide section, not only couples to the higher-order modes but also couples to lower frequency ports.

Far field radiation pattern of the corrugated horn excited with the geometry shown in Figure 3.3 was computed at 18 GHz in the presence of coaxial probes at 6.6 and 10.65 GHz and at 21 GHz in the presence of coaxial probes at 6.6, 10.65 and 18 GHz. It is found that the presence of probes in the lower frequency sections degrades the pattern symmetry and increases cross-polar radiation at higher frequency bands. The cross-polar performance at 18 and 21 GHz deteriorates to around -11 dB as compared to -27 dB for the configuration of Figure 3.2, where no probes are considered at lower frequency bands.

The analysis results for post and probe discontinuities presented in Sections 2.2.1 and 2.2.2 showed that the power coupling to higher-order modes reduces if the depth of the probe (or post) is reduced. It has also been found through simulation and through antenna pattern measurement that the cross-polar performance at 18 and 21 GHz improves if the depth of the probe at 6.6 GHz and 10.65 GHz is reduced from its optimum value for maximum power coupling. Radiation pattern performance improves further if the higher frequency and lower frequency ports of same polarization are decoupled. But, with the reduction of the depth of the probes, the impedance matching deteriorates at 6.6 GHz and 10.65 GHz ports, though there is an improvement of cross-polar performance at 18 and 21 GHz. Thus, the design challenge for this type of multi-frequency mode transducer is to ensure mode purity in the output section ($D_3$) at all the frequency bands and at the same time to achieve optimum power coupling, impedance matching and port to port isolation. The overall design of the multi-frequency OMT is presented in the next section.
3.1.4 Design of Multi-frequency Ortho-mode Transducer

The present design of the mode transducer is based on coupling from primary cascaded circular waveguide sections to output rectangular waveguides WR-137 for 6.6 GHz, WR-75 for 10.65 GHz and WR-42 for 18 and 21 GHz. The schematic of the ortho-mode transducer (a circular to rectangular waveguide end-launcher) at single frequency band at 6.6 GHz is shown in Figure 3.4(a). The ortho-mode transducers at separate frequency bands are cascaded to realize a common 8-port device (Figure 3.4 (b)) operating at all the 4-frequency bands.

![Figure 3.4 (a) Schematic of OMT at single frequency band.](image)

![Figure 3.4 (b) Schematic of a common 8-port OMT at four frequency bands.](image)

The orthogonal ports at the same frequency band have been separated by an axial distance of $\lambda g/2$ and the angular spacing of $90^\circ$ to achieve the desired isolation between the two
ports. As described in the previous section, the reduction of the depth of the probes in the lower frequency waveguide sections from their resonant depths (quarter wavelength) improves the cross-polar performance at higher frequency bands due to reduced power in the higher-order modes.

For example, in the 6.6 GHz orthomode transducer section, 11.6 mm depth of the coaxial probe which is of the order of a quarter wavelength gives good return loss matching but this depth couples sufficient power in the higher order modes at 18 and 21 GHz. The analysis results presented in Sections 2.2.1 and 2.2.2 for post and coaxial probe discontinuities in circular waveguide showed that power coupled to non-desired higher-order modes decreases with the reduction in the depth of the post or the coaxial probe. Therefore, depths of the probes have been reduced in the lower frequency sections in order to minimize higher order modes excited at higher frequencies.

The depth of probes in the 6.6 and 10.65 GHz section was reduced by more than 40 percent from full depth (quarter wavelength). The probe depths were reduced from resonant depths of 11.6 mm to 7.5 mm in 6.6 GHz section, from 7 mm to 4.2 mm in the 10.65 GHz section and from 3.6 mm to 2.5 mm in the 18 GHz section. But the reduction in probe depth reduced the real part and increased the reactive part of the impedance seen by the probe in the circular waveguide. This change in impedance deteriorated the return loss of the signal which was coupled to the circular waveguide from a full-depth probe. For example, the simulated return loss with reduced depth probe was only -4.5 dB as compared to full depth probe where it was better than -17 dB at 6.6 GHz. Although, the method of matching of coaxial line to rectangular waveguide is described in [81], there are no details available in the existing literature on the methodology to achieve matching from circular to rectangular waveguide for multi-frequency operation. In the present design, to improve the return loss, the real part of the impedance seen by the coaxial probe of reduced depth has been matched to a rectangular ridged-waveguide by varying the ridge height and width. The ridged waveguide was further transformed to a rectangular waveguide using stepped ridge waveguide transformer. The heights of different ridge steps are optimized to get optimum matching. Ridged waveguides have been treated in [82]-[84]. The expressions derived by Wolfgang et al. [84] are used to compute cut off wavelength, guide wavelength,
characteristic impedance and design dimensions of the ridged waveguide step transformer in the present design of mode transducer. To make a compact design, the characteristic impedance of the ridged waveguide step transformers has been chosen to follow cosine profile as described in [85]. The reactance due to reduced depth probe was cancelled by using a stub pin in the coaxial section shorting the inner and outer conductor of the coaxial section (like a single stub) as shown in the Figure 3.4(a). The shorting pins at 18 and 21 GHz were not required in the coaxial sections of the mode transducer. The location of the steps of the ridges in the rectangular waveguide with respect to the coaxial section have been found to affect inter-port isolation significantly. For example, a displacement of 0.25 mm of the step from its optimum position of 0.5 mm from the onset of the coaxial section, reduced the isolation of 18 GHz signal with 6.6 GHz port from -41 dB to -10.8 dB. Step locations were optimized for best isolation between lower and higher frequencies.

Modal power distribution and coupling of power to other ports have been computed in the presence of optimized mode transducers consisting of optimized step transformers and lower depth probes giving best return loss at 6.6 and 10.65 GHz. The simulated results for the optimized mode transducers are presented in the Table 3.3, which shows that the maximum power is confined in the dominant TE_{11} mode at all the frequencies. The return loss at 18 and 21 GHz with optimized mode transducers also improved to the order of -15 dB as compared to -10 dB for the case of full depth coaxial probes present at lower frequencies. The return loss at 6.6 and 10.65 GHz was optimized for better than -17 dB. Improved values of port-to-port isolation and reduced values of coupling to higher-order modes have been achieved as shown in Table 3.3.

Table 3.3 The power (dB) in the dominant and higher-order modes in section-D_{T} in the presence of mode transducers.

<table>
<thead>
<tr>
<th>Input signal Frequency (GHz)</th>
<th>Higher-order modes (dB)</th>
<th>TE_{11} Mode (dB)</th>
<th>21 GHz port (dB)</th>
<th>18 GHz port (dB)</th>
<th>10.65 GHz port (dB)</th>
<th>6.6 GHz port (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>-13.03</td>
<td>-1.55</td>
<td>-7.0</td>
<td>-22.0</td>
<td>-27.5</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>-13.01</td>
<td>-0.441</td>
<td>-21.7</td>
<td>-18.0</td>
<td>-41.0</td>
<td></td>
</tr>
<tr>
<td>10.65</td>
<td>-26.38</td>
<td>-0.068</td>
<td>&lt;-99</td>
<td>&lt;-99</td>
<td>-19.1</td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td>-36.0</td>
<td>-0.005</td>
<td>&lt;-99</td>
<td>&lt;-99</td>
<td>&lt;-99</td>
<td></td>
</tr>
</tbody>
</table>
With the optimized mode transducer of reduced depth probe at 6.6 GHz, the predicted mode purity in the TE_{11} mode at 10.65 GHz is of the order of 98.45% and only 0.23 % couples to TM_{01} mode and 1.23% couples to 6.6 GHz port for same polarization. As there is no port in front of 6.6 GHz port, all power is confined in TE_{11} mode at 6.6 GHz.

Modal power distribution and coupling of power to lower frequency ports at 18 GHz have been computed in the presence of mode transducers consisting of optimized step transformers and lower depth probes giving best return loss at 6.6 and 10.65 GHz. The power in the dominant mode at 18 GHz for the optimized mode transducers at 6.6 and 10.65 GHz with reduced depth probes was 90.34% and the total power in the higher order modes was of the order of 5%. In the presence of optimized mode transducers with reduced depth probes at 6.6 and 10.65 GHz, the coupling of 18 GHz signal to 10.65 GHz port was reduced to 1.79% from that of 38.73%, reflected power reduced to 2.9% from that of 9.53% which was with the full-depth coaxial probes (see Table 3.2). Thus, simultaneous objectives of maximizing dominant mode power at 18 GHz, its isolation with lower frequency ports and return loss matching at 6.6, 10.65 GHz frequencies with reduced depth probes were achieved.

Patterns at 18 GHz of corrugated horn (mentioned in section 3.1.1) with simple coaxial probes of reduced heights 7.5 and 4.2 mm in the optimized mode transducer at 6.6 GHz and 10.65 GHz respectively have been plotted. At 18 GHz, the simulated radiation patterns

![Figure 3.5 Radiation patterns at 18 GHz for a horn fed with the OMT of optimized step transformers and reduced depth probes at 6.6 and 10.65 GHz.](image_url)
of a horn fed by the OMT of optimized step transformers and reduced depth probes are given in Figure 3.5. Simulated results show 9 dB better cross-polar radiation (-20 dB) performance of the horn fed with the OMT of reduced depth probes than the cross-polar radiation (-11dB) achieved with full depth probes in the lower frequency sections. This improvement is due to the higher isolation with lower frequency ports and less coupling to higher order modes. The predicted mode purity in the dominant TE_{11} mode at 21 GHz is of the order of 70 % with optimum isolation achieved with lower frequency ports. The power in the higher-modes at 21GHz resulted into asymmetry in the predicted co-polar patterns and the cross polar radiation level was of the order of -18 dB in the presence of all the lower frequency ports. To keep the coaxial probe in the center of coaxial line and to maintain its orthogonality with respect to other port, a dielectric bead was used at the base of the coaxial probe in the 6.6 GHz coaxial section.

3.1.5 Measured and Simulated Results of 8-Port Orthomode Transducer

The simulated and measured return loss for 6.6 GHz frequency and isolation between orthogonal ports is presented in Figure 3.6. The measured isolation between orthogonal ports at 6.6 GHz is better than -36 dB at the specified bandwidth of 250 MHz. In Figure 3.6, S_{11} and S_{22} represent the scattering parameters for return loss at port-1 and port-2 (see Figure 3.4(a)) and S_{12} represents the scattering parameter for isolation between ports 1 and 2. Port1 and port 2 are the orthogonal rectangular waveguide ports of OMT (see Figure 3.4(a)).

![Figure 3.6 Return loss for 6.6 GHz circular to rectangular waveguide mode transducer for both the orthogonal ports.](image-url)
At 10.65 GHz, -15 dB return loss bandwidth of 300 MHz is achieved by using circular to ridged rectangular waveguide mode transducer. Slightly shifted return performance towards higher frequency was achieved at this frequency as shown in Figure 3.7. Measured decoupling of -18 dB as shown in Figure 3.8 was achieved for 10.65 GHz signal with 6.6 GHz coaxial probe. An isolation of better than -29 dB was achieved between orthogonal ports over the band.

![Figure 3.7](image1.png)  
**Figure 3.7** Return loss for 10.65 GHz circular to rectangular waveguide mode transducer for both the orthogonal ports.

![Figure 3.8](image2.png)  
**Figure 3.8** Measured isolation of 10.65 GHz signal with 6.6 GHz coaxial probe port with parallel polarization.
The measured results for 18 GHz OMT are shown in Figure 3.9. The Figure 3.9 presents return loss at the orthogonal ports of the mode transducer at 18 GHz. When the probe depth at 18 GHz is 2.5 mm, -15 dB return loss bandwidth obtained is 300 MHz. The measured isolation between orthogonal ports at 18 GHz is of the order of -25 dB over the band. The measured isolation of 18 GHz signal is better than -30 dB and -20 dB with 6.6 GHz and 10.65 GHz ports respectively for same polarization as shown in Figure 3.10.

Figure 3.9 Measured return loss and isolation for 18 GHz OMT.

Figure 3.10 Measured isolation of 18 GHz signal with 6.6 GHz and 10.65 GHz ports.
At 21 GHz, with the probe depth of 3.1 mm, -15 dB return loss bandwidth of 360 MHz was obtained as shown in Figure 3.11. The measured isolation between orthogonal ports is of the order of -25 dB over the band. As shown in Figure 3.12, the isolation of 21 GHz signal with 6.6 and 10.65 GHz was better than -20 dB over the band. The measured isolation of 21 GHz signal with 18 GHz port was only -7 to -10 dB over the band, which could not be improved due to the comparable size of OMT at 21 GHz to that of 18 GHz. The poor isolation adds to increased insertion loss at 21 GHz. The measured insertion loss of the OMT is 0.5, 0.7, 1.1 and 1.6 dB at 6.6, 10.65, 18 and 21 GHz, respectively.

Figure 3.11 Measured return loss and isolation for 21 GHz OMT.

Figure 3.12 Measured isolation of 21 GHz signal with other lower frequency ports for parallel polarization.
The photograph of the developed 8-port OMT [86] for which the simulated and measured results were presented in Figures 3.6-3.12, is shown in Figure 3.13.

![Photograph of 8-port common OMT](image)

Figure 3.13  Photograph of 8-port common OMT at 6.6, 10.65, 18 and 21 GHz.

### 3.2 Mode Transducer at Three Frequency Bands

Altimeter needs a nadir looking radiometer operating at $18.7 \pm 0.2$ GHz, $23.8 \pm 0.3$ GHz and $36.5 \pm 0.5$ GHz frequencies for atmospheric correction. The system requirement is of single linear polarization at these three frequency bands. Since, the effect of discontinuities as described in previous sections of this chapter is envisaged to be more stringent at the highest frequency of 36.5 GHz, it is worthwhile to investigate the modal behavior at the highest frequency in the presence of lower frequency ports and to arrive at an optimum design which yields optimum performance at all the frequency bands. Following the concept and design methodology developed for four frequency OMT (Section 3.1), the development of tri-frequency mode transducer has been carried out. The simulation and measured results are presented.
Three cases have been studied for three frequency common mode transducer and are discussed in order.

**Case 1:** The configuration for case-1 is shown in Figure 3.14(a). The performance is simulated at 36.5 GHz in the presence of mode transducers at 23.8 GHz and 18.7 GHz. Here, all ports at 18.7, 23.7 and 36.5 GHz are aligned i.e., polarization matched. In this case, the return loss at 36.5 GHz, is -15.14 dB. The signal at 36.5 GHz is isolated from the 23.8 GHz port by -17.61 dB and from by 18.7 GHz port by -21.46 dB. From the data presented in Table 3.4, it is clear that more power couples in the higher-order modes at the aperture at 36.5 GHz.

**Case 2:** The configuration for case-2 is shown in Figure 3.14 (b). The performance is simulated at 36.5 GHz in the presence of mode transducers at 23.8 GHz and 18.7 GHz. Here, ports at 18.7, 23.7 are aligned and orthogonal to 36.5 GHz. In this case return loss at 36.5 GHz is -11.04 dB. The signal at 36.5 GHz is isolated from the 23.8 GHz port by -70.98 dB and from 18.7 GHz port by -58.85 dB. The Table 3.4, shows that more power couples in the higher-order modes at the aperture at 36.5 GHz.

**Case 3:** The configuration is shown in Figure 3.14 (c). The performance is simulated at 36.5 GHz in the presence of mode transducer at 23.8 GHz and 18.7 GHz. Here, ports at 36.5, 23.7 are aligned and orthogonal to 18.7 GHz as shown in Figure 3.14 (c). In this case return loss at 36.5 GHz is -14.29 dB. The signal at 36.5 GHz is isolated from the 23.8 GHz port by -18.45 dB and from 18.7 GHz port by -38.65 dB. The Table 3.4, shows that maximum power (-1.15 dB) couples in the dominant \( \text{TE}_{11} \) mode and minimum power couples in the higher order modes at the aperture at 36.5 GHz in the presence of all the ports. This configuration gives the optimum performance at all the frequencies, therefore, this can be considered as final design configuration. This configuration has been designed, developed and measured for electrical performance. The modal analysis results for this configuration show that the return loss at 23.8 GHz is -17.49 and the isolation of 23.8 GHz signal with 18.7 GHz is -58.61 dB. Maximum power couples in the \( \text{TE}_{11} \) mode which is of the order of -0.095 dB and minimum power is in the higher-order mode. This configuration
gives maximum power in the desired TE$_{11}$ mode at 18.7 GHz and negligible power in the higher-order modes which are not supported in the outermost section. Simulated and measured performance of the cascaded mode transducer (Figure 3.14 (c)) operating at all the three frequency bands are given in the next section.

![Figure 3.14](image)

Figure 3.14  Different configuration to combine waveguide sections at 3 frequencies.

Table 3.4  Modes at the aperture of the cascaded mode transducer at 36.5 GHz.

<table>
<thead>
<tr>
<th>Mode names</th>
<th>TE$_{11}$</th>
<th>TM$_{01}$</th>
<th>TE$_{21}$</th>
<th>TE$_{01}$</th>
<th>TM$_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modal Amplitude (dB) for Fig.3.14 a</td>
<td>-1.37</td>
<td>-8.82</td>
<td>-11.04</td>
<td>-48.21</td>
<td>-55.46</td>
</tr>
<tr>
<td>Modal Amplitude (dB) for Fig.3.14 b</td>
<td>-1.36</td>
<td>-50.41</td>
<td>-7.33</td>
<td>-38.10</td>
<td>-52.99</td>
</tr>
<tr>
<td>Modal Amplitude (dB) for Fig.3.14 c</td>
<td>-1.15</td>
<td>-23.33</td>
<td>-7.74</td>
<td>-37.60</td>
<td>-48.11</td>
</tr>
</tbody>
</table>

The measured and simulated performance of the combined three frequency mode transducer (Figure 3.14 (c)), which gave optimum performance in terms of return loss, isolation and higher-order mode coupling have been found out. The results are compared with the performance at individual mode transducers. Figures 3.15, 3.16 and 3.17, show the return loss performance at 18.7, 23.8 and 36.5 GHz. The performance at 23.8 GHz frequency band is slightly affected due to the presence of 18.7 GHz port in front of 23.8
GHz port as compared to the performance of individual mode transducer at 23.8 GHz. The performance at 36.5 GHz is more affected by the presence of two lower frequency ports at 18.7 GHz and 23.8 GHz in front of the 36.5 GHz port. Measured isolation of 36.5 GHz signal with 23.8 GHz port is of the order of 20 dB over 80 percent of the desired frequency band and the isolation with 18.7 GHz port is of the order of −25 dB as shown in Figure 3.18. The measured isolation of 23.8 GHz signal with 18.7 GHz port is of the order of −50 dB as shown in Figure 3.19.
Figure 3.17 Simulated and measured return loss at 36.5 GHz.

Figure 3.18 Measured and simulated isolation performance of 36.5 GHz signal with 18.7 and 23.8 GHz ports.
Figure 3.19 Measured and simulated isolation performance of 23.8 GHz signal with 18.7 GHz port.

Figure 3.20 Tri-frequency mode transducer at 18.7, 23.8 and 36.5 GHz.

The photograph of the tri-frequency mode transducer is shown in Figure 3.20.
3.3 Conclusion

A novel design of four frequency band OMT to feed a common corrugated horn has been presented. In the multi-frequency environment, the methods of controlling power in the higher-order modes and improving isolation of higher frequencies with lower frequency ports are described. Modal analysis has been performed to estimate the effects of symmetrical step, taper and asymmetrical probe discontinuities in the main waveguide particularly at higher frequencies [86], [87]. An optimum configuration of multi-frequency OMT yielding desired isolation of orthogonal ports, isolation of higher frequencies with lower frequency ports of same polarization and maximum power in the dominant TE_{11} mode has been obtained [86]. As it was not possible to fabricate the OMT device using a single piece, it was fabricated in a number of pieces and assembled to make the 8-port device. The slight deviation of the measured data from simulated data may be attributed to fabrication tolerances and minor assembly and alignment errors. The modal analysis based design approach presented in this paper may be applied to the design of multi-frequency ortho-mode transducers at other frequency bands. The multi-frequency design concept has been successfully utilized to develop a mode transducer at 18.7, 23.8 and 36.5 GHz.

In order to find out the radiation characteristics of the multi-frequency mode transducers, it became imperative to realize composite feeds operating at widely separated frequency bands. These feeds are discussed in Chapter 4.