An Electronically Controlled Polarization Generator at Ka-band

Steven R. Nichols
Product Engineering
MI Technologies
Suwanee, Georgia, USA
snichols@mitechnologies.com

***Abstract*— As part of a target simulator, a linearly polarized signal was required with a variable tilt angle that could be controlled electronically and changed at a 1 kHz rate. The signal simulates the effect of rapid polarization changes that a missile might encounter in real time during flight.**

Tilt angles can be varied by adjusting the amplitude of the vertical and horizontal inputs to an orthomode transducer. To produce good cross-polarization, independent phase adjustments are also required. However, microwave components available in the 33.4 – 36 GHz operating range were inadequate to achieve the desired performance.

A novel approach was developed to downconvert the input signal to a lower frequency range and use vector modulators available in the lower band to produce the appropriate phase and amplitude changes in each path, then upconvert back to the desired operating frequency to drive the orthomode transducer. A device was built and tested using this approach.

A calibration and measurement procedure was developed to determine the vector modulator input settings that produced the most accurate tilt angles and best cross-polarization performance. By iteratively measuring cross-polarization and tilt angle, then adjusting the vector modulator controls, a tilt angle accuracy of +/-1 degree was achieved with a cross-polarization of -25 dB, exceeding the required performance.

By implementing the architecture described, both the phase and amplitude of the horizontal and vertical signals to the orthomode transducer can be controlled. In addition to linearly polarized signals, other types of polarization signals can also be generated, including left-hand and right-hand circular, as well as the general case of elliptical polarization.

Index Terms*— *Axial Ratio, Cross-Polarization, Measurement, Polarization, Tilt Angle

I. INTRODUCTION

The polarization of an electromagnetic wave may be described as an ellipse formed by the electric field when viewed along its axis of propagation [2] as illustrated in Figure 1. The tilt angle is commonly defined as the angle between the major axis of the ellipse and the horizontal axis of the coordinate system. The axial ratio is defined as the ratio of the major to minor axes of the polarization ellipse [3]. The term cross-polarization refers to the signal in the minor axis. In this paper, where a magnitude for cross-polarization is expressed, it is the inverse of the axial ratio. Linear and circular polarizations are special cases of the ellipse where the magnitude of the cross-polarization is 0 and 1 respectively.

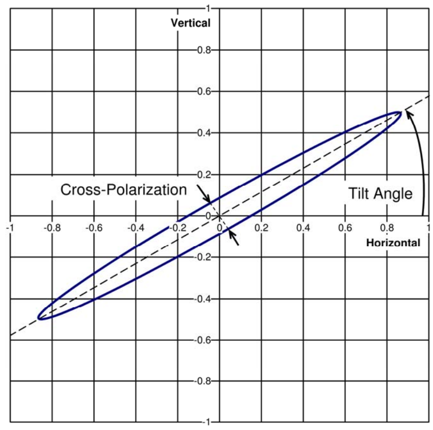

Figure 1 – Polarization Ellipse

By controlling the amplitude and phase of the horizontal and vertical inputs to an orthomode transducer, various polarization effects can be produced, including linear, circular, and elliptical polarization. The amplitude relationship between the two inputs largely determines the tilt angle, while the phase relationship determines the axial ratio. For linear polarization, the phase relationship needs to be 0 or 180 degrees, and for circular polarization, 90 or 270 degrees is required.

The conceptual block diagram of a hardware implementation that supports various polarization effects is shown in Figure 2.

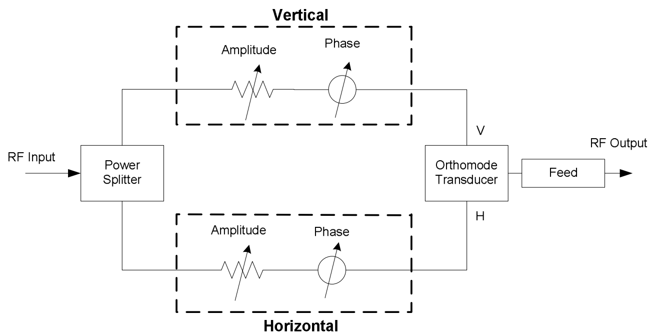

Figure 2 – Conceptual Block Diagram

In Figure 2, an externally supplied RF input signal is split into separate vertical and horizontal paths. Each path has independent adjustments for amplitude and phase. By varying the relative amplitudes and phases of each path, all types of polarizations can be generated.

II. Assessment of Requirements

For this particular project, the critical performance requirements and design goals are listed below. With some additional analysis, these requirements can be used to determine the resolution and accuracy needed for the attenuator and phase shifter controls.

- Frequency range: 33.4 – 36 GHz
- Polarization: Linear
- Tilt angle range: 0 – 180 degrees
- Resolution: 10 degrees or better
- Cross-polarization:
  -15 dB (-20 dB design goal) at center frequency
  -13.5 dB across +/-400 MHz bandwidth
- Update rate: 1.5 KHz minimum
- Latency: 10 uS maximum

Axial ratio is dependent on the both the tilt angle and the phase delta between the horizontal and vertical polarized signals according to the equation below [5]:

$$\text{Axial Ratio} = \frac{(\tan\delta)(\sin(2\beta))}{-1+\sqrt{1+[(\tan\delta)(\sin(2\beta))]^2}}$$

Where:

δ = delta phase between signals

β = tilt angle

The graph in Figure 3 shows axial ratio as a function of phase delta between the horizontal and vertical signals at a 45 degree tilt angle.

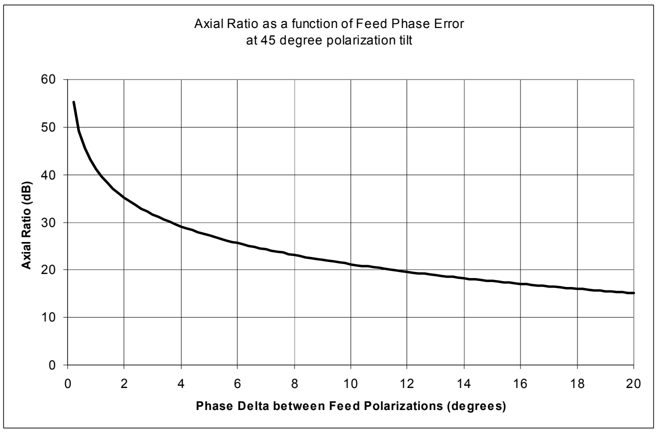

Figure 3 – Effect of Phase on Axial Ratio

To achieve an axial ratio of 15 dB, the phase relationship between the horizontal and vertical paths must not exceed 20 degrees. To achieve the axial ratio design goal of 20 dB, the phase relationship must not exceed 11 degrees, so this was established as the phase error budget. If the phase is to be adjustable, the resolution of the phase shifter would need to be smaller than 11 degrees and would ideally approach 1 degree or better.

Figure 4 shows a graph of axial ratio as a function of tilt angle with 11 degrees of phase error between orthomode transducer ports. Note that the largest error occurs at 45 degrees. (The same error also repeats at a 135 degree tilt angle.)

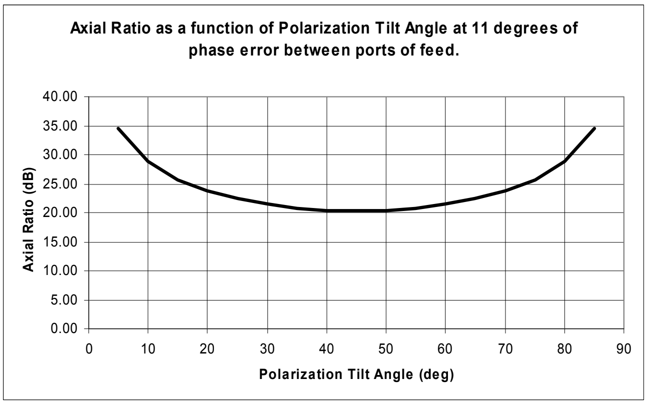

Figure 4 – Axial Ratio Sensitivity to Tilt Angle

The ideal scale factors required to generate 0 to 180 degree tilt angles are shown in Table I. The horizontal and vertical amplitudes vary with the cosine and sine of the tilt angle respectively. Negative normalized scale factors indicate a 180 degree phase shift between the vertical and horizontal signals instead of 0 degrees. The table also includes the attenuator values in dB required to accomplish these scale factors.

TABLE I. IDEAL SCALE FACTORS

Tilt Angle (degrees)	Normalized Factor		Normalized Attenuation	
	Horizontal	*Vertical*	*Horizontal (dB)*	*Vertical (dB)*
0	1.0000	0.0000	0.00	-60.00*
10	0.9848	0.1736	-0.13	-15.21
20	0.9397	0.3420	-0.54	-9.32
30	0.8660	0.5000	-1.25	-6.02
40	0.7660	0.6428	-2.31	-3.84
45	0.7071	0.7071	-3.01	-3.01
50	0.6428	0.7660	-3.84	-2.31
60	0.5000	0.8660	-6.02	-1.25
70	0.3420	0.9397	-9.32	-0.54
80	0.1736	0.9848	-15.21	-0.13
90	0.0000	1.0000	-60.00*	0.00
100	-0.1736	0.9848	-15.21	-0.13
110	-0.3420	0.9397	-9.32	-0.54
120	-0.5000	0.8660	-6.02	-1.25
130	-0.6428	0.7660	-3.84	-2.31
140	-0.7660	0.6428	-2.31	-3.84
150	-0.8660	0.5000	-1.25	-6.02
160	-0.9397	0.3420	-0.54	-9.32
170	-0.9848	0.1736	-0.13	-15.21
180	-1.0000	0.0000	0.00	-60.00*

*Practical limitation of available components

Ideally, phase-invariant digitally controlled attenuators with better than 0.1 dB resolution and accuracy could be used to control tilt angle. However, so-called phase-invariant attenuators have enough phase variation as to exceed the 11 degree phase error budget. Therefore, a digitally controlled phase shifter must be used to compensate for phase variations whenever the attenuator is changed. The best phase shifter that could be found in this frequency range at that time was 5 bits, giving a resolution of 11.25 degrees and an accuracy of only 6 degrees. This was inadequate for the performance required.

Therefore an alternate concept was developed (see Figure 5). By block down converting the 33.4 – 36 GHz input signal to 6.2 – 8.8 GHz, vector modulators could be used in each path to control amplitude and phase independently. Subsequent block up conversion brings the signals back exactly to the original frequency by using the same local oscillator (LO) for both up and down conversion.

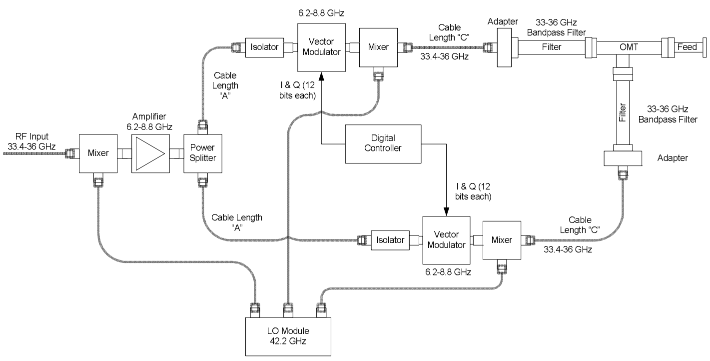

Figure 5 – Alternate Concept

The vector modulators chosen do not inherently have sufficient accuracy, but they have 12-bit resolution, are repeatable, and can be calibrated to the measurement accuracy of laboratory test equipment. It was estimated that by using a network analyzer, the vector modulators could be characterized to within +/- 3 degrees of phase and +/- 0.3 dB of amplitude.

With this design concept, a phase offset due to differing electrical path lengths of the vertical and horizontal paths is likely to be present, but it can be mitigated by changing the vector modulator settings. However, as frequency is varied without changing vector modulator settings, the difference in path lengths will cause additional phase shift between the horizontal and vertical sections, resulting in reduced axial ratio performance.

Phase matched cables are used to minimize this effect. An error budget was established to allow a difference of 0.75 lambda (~1/4") between the two paths, which yields 6 degrees of phase shift for a frequency change of 800 MHz.

Adding up these phase errors and comparing to the 11 degree error budget showed that the axial ratio performance should be achievable:

Vector Modulator calibrated phase error:	3 degrees
Phase change over 800 MHz:	6 degrees
Total:	9 degrees
	(2 degrees of margin)

Cross-polarization: -22 dB (at 45 degree tilt angle)

Furthermore, the vector modulator calibrated phase error can be further reduced if needed by making axial ratio measurements in the targeted system and fine-tuning the vector modulator inputs.

III. Characterization of Vector Modulators

It was anticipated that the vector modulators would have sufficient non-linearities that a simple I/Q to phase/amplitude calculation would not be accurate enough to produce the desired results. The vector modulators must be characterized to determine the appropriate I/Q settings to be used. The 11 ideal magnitudes needed are well defined. However, phase adjustments would need to be made during testing. Therefore, it was decided to generate tables of I/Q settings for each vector modulator in 1 degree phase increments over the 360 degree range for each of 11 magnitudes. Since these settings need to change with frequency, the measurements were repeated in 0.1 GHz steps for a total of 27 frequencies. By creating tables of I/Q settings ahead of time, adjustments during testing could be performed much more quickly.

Using a network analyzer, measurements were made of the 2 vector modulators to be used in this system. The digital I and Q input ports of the vector modulators were varied across the full 12-bit range to produce a 135 x 135 point grid. These measurements were made at 0.1 GHz frequency steps across the band. The complete measurement process took several days with automated software.

The results were normalized and the actual I/Q values were plotted against the ideal I/Q values. The underlying grid of points is plotted beneath idealized magnitude circles in Figure 6. The ideal pattern would be perfectly rectangular with evenly spaced points, but it appears as a distorted square with unequal spacing between points. Errors in the vector modulators cause the pattern to be distorted, especially near the quadrant boundaries and the corners.

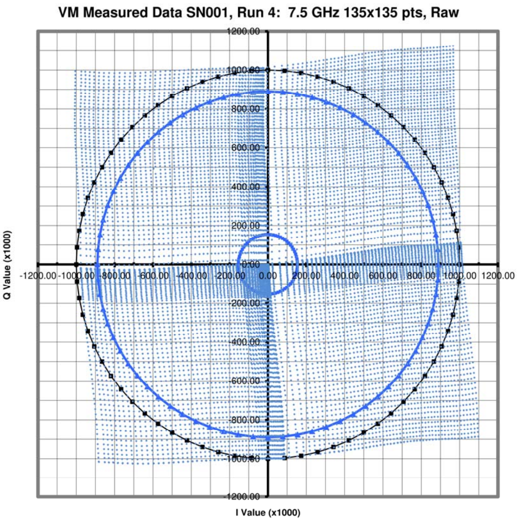

Figure 6 – Vector Modulator Measurements

The outer circle indicates the largest magnitude signal that could be produced through the vector modulators. The slightly smaller circle is for a small reduction in magnitude, and the innermost circle represents a much smaller magnitude. Points along these circles represent various phase settings that might be chosen, depending on the desired polarization effect. The intersection of points on each circle with the underlying grid defines the I/Q settings to be used to produce the desired magnitude and phase along the circle.

Because of limited resolution of the data collected, interpolation was used to improve the accuracy of the tables. Bilinear interpolation was applied to the measured data to produce vector modulator I/Q settings for 11 magnitudes, 360 phase settings, and 27 frequencies.

Tables of these I/Q settings were created and stored in a database for access later during the calibration and test process. By providing frequency and phase offset, the settings for all tilt angles are provided for both the horizontal and vertical vector modulators.

IV. CALIBRATION AND TEST PROCESS

After constructing the polarization generator described in Figure 5, its characteristics were measured in a test chamber. A calibration and test process was developed during which the I/Q settings for the vector modulators were selected and refined to optimize performance under various conditions. The resulting performance characteristics were recorded and compared to the requirements.

The calibration and test procedure is divided into 4 steps. It results in parameter settings for a single frequency, so it must be repeated for each frequency or band of interest. For purposes of demonstration, three frequencies were selected, one at mid-band and one each at 400 MHz from the bottom and top of the band. These frequencies are 33.8 GHz, 34.7 GHz, and 35.6 GHz.

Step 1: Estimate the phase difference between the horizontal and vertical signals at the point they combine in the orthomode transducer.

- Using the tables previously created from measuring the vector modulators, apply initial settings for a 45 degree tilt angle. Both the horizontal and vertical vector modulators will be set to the same amplitude. The phase is somewhat arbitrary, as long as the selected phase is the same for both vector modulators. Since the non-linearities in the vector modulator are worse at the quadrant boundaries, it is recommended to select a phase of 30 to 60 degrees.
- Once the vector modulators have been set, measure the tilt angle and axial ratio under boresight conditions. Any number of measurement techniques may be used, but this project used the polarization pattern method [4].
- By setting both paths to the same phase, whatever phase offset may exist between the two paths will cause a reduction in axial ratio, and any amplitude differences will cause a shift in the tilt angle. Knowing the axial ratio and tilt angle, the phase offset can be estimated using a graphical method [5].

Step 2: Adjust the horizontal vector modulator settings to remove the phase offset between the horizontal and vertical paths.

- Using the tables previously created from measuring the horizontal vector modulator, subtract the estimated phase offset from the initial phase setting, and look up the new vector modulator settings. Apply these to only the horizontal path, leaving the vertical path with its initial phase setting.
- Ideally, this will reduce the phase offset to 0 degrees (for linear polarization).

Step 3: Measure tilt angle and axial ratio for all tilt angles from 0 to 180 degrees in 10 degree steps.

- For each tilt angle, load the vector modulator settings for the vertical path from step 1 and the horizontal path from step 2.
- Measure tilt angle and axial ratio under boresight conditions.
- Record the results.

Step 4: Fine tuning of vector modulator settings.

- If performance is satisfactory, there is no need for additional fine tuning. However 1 or 2 iterations of a few outlying points can improve results substantially.
- Interpolate between the measured results to adjust the vector modulator settings as needed to improve tilt angle accuracy and axial ratio.
- Record the final I/Q settings and results achieved.
- Although this process can be quite tedious, it can be adapted to the level of performance required. For extreme performance, one could fine tune I/Q settings for every frequency and tilt angle to achieve excellent axial ratios and tilt angle accuracy and axial ratio. The results shown here are achieved using 3 frequencies and a moderate amount of fine tuning.

V. Performance Achieved

The calibration and test process was performed for 33.8 GHz, 34.7 GHz, and 35.6 GHz. The resulting measured tilt angle error is shown in Figure 8 with each frequency plotted as a separate line. Tilt angle resolution of 10 degrees with an accuracy of +/-1 degree was achieved.

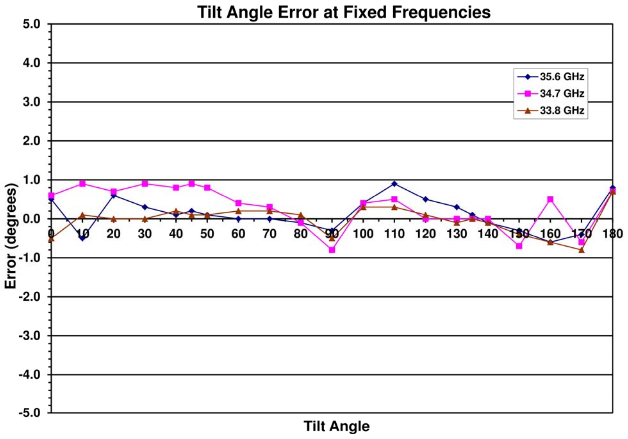

Figure 7 – Tilt Angle Error

For the same 3 frequencies, cross-polarization performance is plotted for each tilt angle in Figure 9. The -20dB design goal was exceeded in all cases.

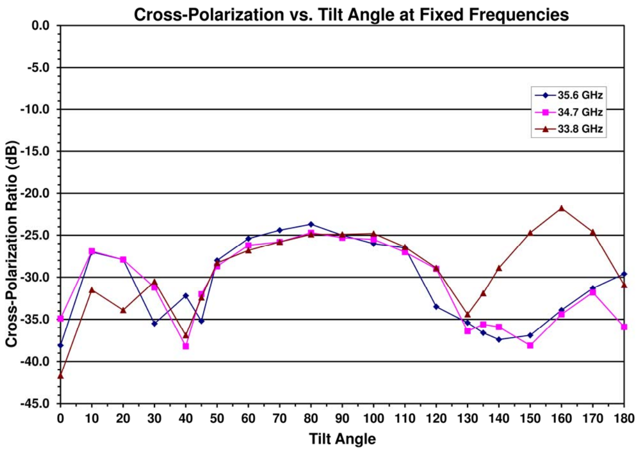

Figure 8 – Cross-polarization Performance

Using the settings for these same 3 frequencies, a frequency sweep was performed at 45 and 135 degree tilt angles. The results are combined to create 3 bands that cover the entire frequency range with 1 set of vector modulator settings for each band. The plot in Figure 10 illustrates the band breaks and performance. As expected, there does appear to be some path length difference or other frequency dependent phase variation between the two paths that causes deterioriation of the cross-polarization performance as the frequency is shifted away from the calibration frequency. However, cross-polarization performance of -15dB or better is achieved, which exceeds the requirement of -13.5dB cross-polarization over a +/-400 MHz range.

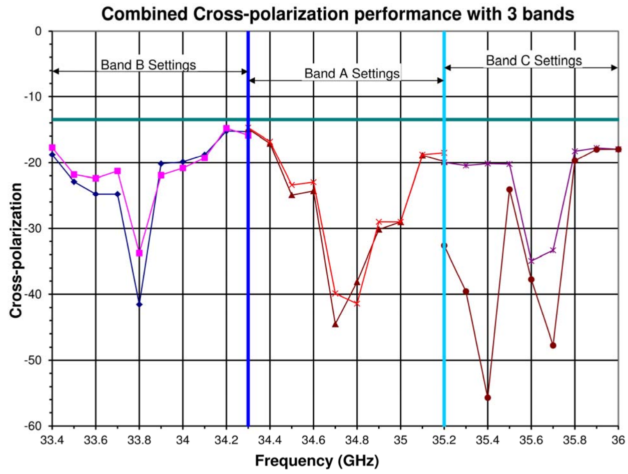

Figure 9 – Cross-polarization Bandwidth

VI. Final Remarks

All requirements for generating linearly polarized signals were met or exceeded, including update rate and latency. Still better performance is possible by using more calibration frequencies for better cross-polarization, more test points for better tilt angle resolution, and/or more time fine tuning for better accuracy. And using unique vector modulator settings for every test frequency would provide the optimum performance.

This design also has the capability of providing right and left circular polarization by adjusting phase offset between the horizontal and vertical paths to +/- 90 degrees. The general case of elliptical polarization can also be supported.

Acknowledgements

The author wishes to thank John McKenna, MI Technologies, who assisted in developing and performing the calibration process, including creating an updated nomograph for estimating horizontal/vertical phase offset from tilt angle and axial ratio measurements (based on prior art [5]).

References

[1] David Wayne, et al., "Portable RF Target Simulator", Proceedings of the Antenna Measurement Techniques Association, 2009.

[2] Warren L. Stutzman and Gary A. Thiele, Antenna Theory and Design, 2nd Edition, John Wiley & Sons, 1998, pp. 48-52.

[3] IEEE Standard Definitions of Terms for Antennas", IEEE standard 145-1993.

[4] T. G. Hickman, J. S. Hollis, and L. Clayton, Jr., "Polarization Measurements", in Microwave Antenna Measurements, Scientific Atlanta, Atlanta, GA, 3rd edition, November, 1985, pp. 10-1 through 10-38, Available from MI Technologies, 1125 Satellite Blvd, Suite 100, Suwanee, GA.

[5] Millett G. Morgan and W. Raymond Evans, Jr., "Synthesis and Analysis of Elliptic Polarization Loci in Terms of Space-Quadrature Sinusoidal Components", Proceedings of the I.R.E., 1951, pp. 552-556.