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A 35 GHZ ELECTRONICALLY STEERED LINE ARRAY

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ABSTRACT

This paper details the design and evaluation of a Ka-band hybrid PIN diode phase shifter and its subsequent assembly into a phase steered line array with printed dipole radiating elements. Measured data are presented indicating a 3.9 dB phase shifter insertion loss at 35 GHz and beam-steering characteristics for the line-array that are commensurate with the phase shifter performance. The power handling capability is estimated to be in excess of 29 Watts CW. This work, we believe, demonstrates the feasibility of millimeter wave phased arrays based on solid-state technology.

INTRODUCTION

There are many challenges associated with the realization of an active millimeter-wave phased array, one in particular being that of meeting the severe constraints on component dimensions. For a planar phase steered array the optimum layout and spacing of the radiating elements will be dictated by the required angular coverage and grating lobe suppression. A Ka-band design, for instance, might typically require a triangular element grid with an element pitch of the order of 0.20 inches, and thus be dependent upon finding a T/R module that not only satisfies a tight electrical specification but that also has a severe limitation on its overall size, particularly if it is to be mounted directly behind a radiating element. A T/R module typically would contain RF amplifiers, switches, and phase shifters - the actual architecture being dependent upon the functional requirements of the system. The phase shifter is usually the largest of these components and is therefore significant in determining the minimum module size.

Our objective was to demonstrate feasibility of millimeter-wave active phased arrays by focusing on the problem of realizing a low-loss four-bit diode phase shifter with size and performance constraints typical of a Ka-band planar array To this end, a hybrid phase shifter was demonstrated in microstrip using silicon PIN diodes and subsequently evaluated within a six-element phase steered line-array.

CIRCUIT DESIGN

Our design approach for a four-bit phase shifter employed loaded-line networks for the 22.5° & 45° bits and hybrid coupled reflection networks (using a ratrace coupler) for the 90° & 180° bits (Fig.1). This approach avoids the uncertainties of lumped element equivalent circuit models and also offers a design flexibility in a common switching device for each bit, thereby minimizing the number of device models required and simplifying diagnostic measurements. Frequency-dependent s-matrix microstrip discontinuity models were employed, derived from a fullwave analysis of a planar waveguide microstrip model.[1] This model is considered essential for millimeter-wave circuit design as many of the Super-Compact discontinuity models for microstrip are not valid above 18 GHz. Microstrip on 0.010 inch alumina was selected as the transmission medium due to its compatibility with integrated printed dipole radiating elements and the inherent small size offered by a high dielectric constant medium. A silicon PIN diode was selected as the switching device.

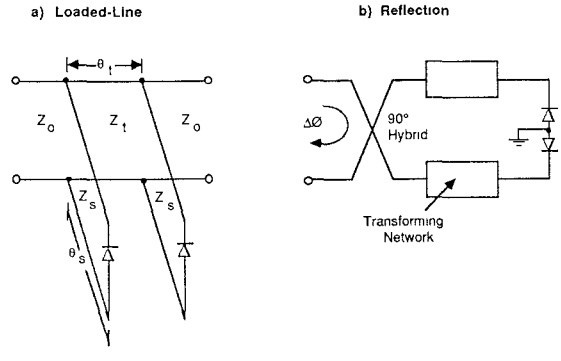

Figure 1. Selected Phase Shifting Networks

Analysis and optimization of each bit was performed using Super-Compact but incorporating s-parameters for each discontinuity as calculated from a planar waveguide model. A simple R-C model was assumed for the device with a capacitance of 0.1pF and a cut-off frequency ($F_{co} = 1/2\pi RC$) of 1600 GHz. For practical operation, a parallel coupled-line DC break and Hi-Lo impedance bias

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network were also designed. A theoretical insertion loss of 0.8 dB was assumed for the DC breaks and connecting lines required by a four-bit design. The theoretical performance of each phase shifter is detailed in Table 1 and indicates a four-bit insertion loss of 2.3 dB for $F_c = 1600$ GHz. Also shown in the table are the theoretical insertion loss figures assuming a worst case F_c of 1000GHz - note that this gives an increase of only 0.6 dB. Analysis of the VSWR variation for all phase states across a 2 GHz bandwidth predicts a maximum VSWR of 1.39:1.

Table 1. Theoretical performance of individual bits

Frequency: 35 GHz
Bandwidth: 2.0 GHz
Diode Capacitance: 0.1 pF

Phase Shift (deg.)	Circuit type	Insertion Loss (dB)		Max SWR
		$F_c = 1.0$THz	$F_c = 1.6$THz	
22.3 ± .01	Loaded-Line	0.18 ± .02	0.12 ± .02	1.14
45.1 ± .09	Loaded-Line	0.32 ± .06	0.21 ± .05	1.20
90.2 ± .02	Reflection	0.67 ± .09	0.50 ± .06	1.15
180.0 ± 2.6	Reflection	0.99 ± .22	0.70 ± .15	1.30
Total Loss =		2.16 ± .39	1.53 ± .28	

Add **0.8 dB** to total loss for DC breaks (0.5dB) and 15mm of microstrip (0.3dB).

The substrate patterns for the 22.5°/45° and 90°/180° bits, shown in Figures 2 & 3 respectively, were configured for edge-mounted diodes to avoid unnecessary substrate profiling. The prototype used two 90° bits to form a 180° bit. The cascade measured slightly over 1.0 inch long and, with the addition of diodes, measured 0.18 inches wide (comfortably within our 0.2 inch maximum width constraint). Further length reduction of at least 25% is possible by using a true 180° bit, and width reduction can be achieved with a revised layout incorporating substrate holes.

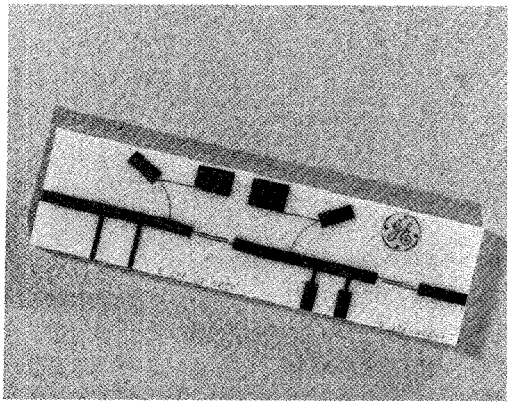

Figure 2. 22.5°/45° Phase Shifter Substrate

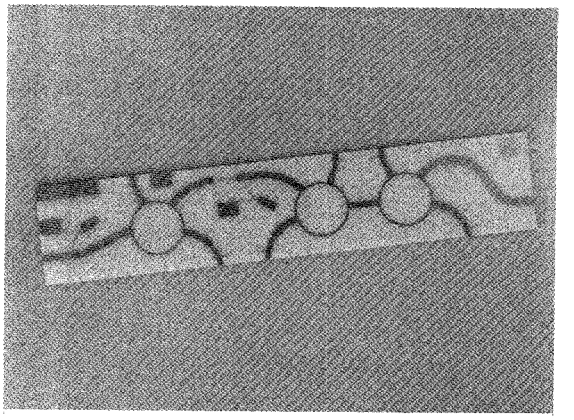

Figure 3. 90°/180° Phase Shifter Substrate

PHASE SHIFTER MEASUREMENTS

Each phase bit was evaluated in a fixture with co-axial K-connector launches. A single launch onto 10 mil alumina was evaluated in a back-to-back configuration using a microstrip sliding load; measured data indicate a return loss of better than 20 dB up to 38 GHz. Measured phase shift and loss of each phase shifter bit are shown in Figures 4 & 5 respectively and summarized in Table 2. The phase shift data is 10-20% higher than design, however diode measurements indicated a reverse bias capacitance that deviates approximately 10% from the model. Measurements of the 22.5°/45° cascade indicate that the loss variation between phase states at 35 GHz is small (Fig.6), less than ±0.08 dB for this arrangement. The insertion loss of the 90° bit was optimized with tuning stubs, but this introduced a slope to its phase response and increased its phase shift from 101° to 110° at 35 GHz. Diagnostics indicated that the coupler was not optimum, and the performance of this type of phase shifter is critically dependent upon the coupler characteristics.[2]

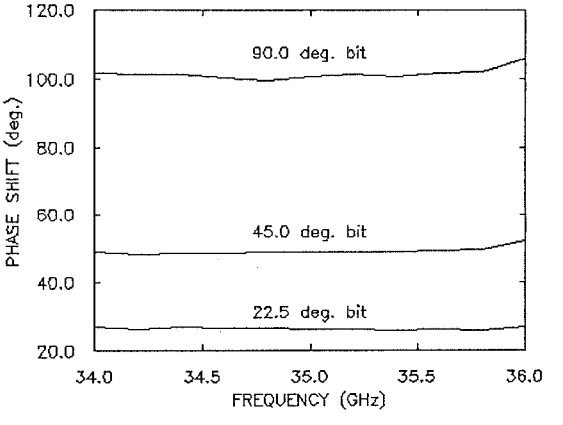

Figure 4. Measured Phase Shift of Individual Bits

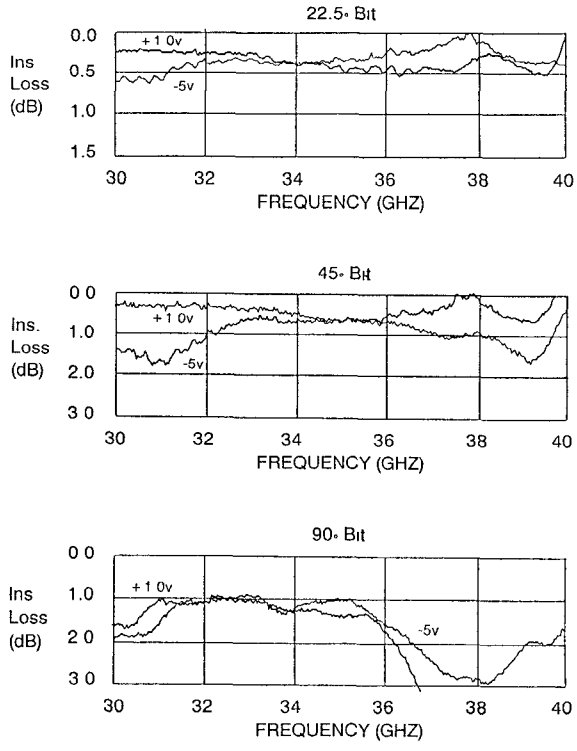

Figure 5. Measured Insertion Loss of Individual Bits

Table 2. Phase Shifter Performance Summary at 35 GHz

Design Phase Shift (deg.)	Circuit Type	Insertion Loss (dB)		Measured Phase Shift (deg)
		Theory	Measured	
22.5	Loaded-line	0.12 ± .02	0.36 + .04	27
45.0	Loaded-line	0.21 ± .05	0.65 ± .05	49
22.5/45.0*	Loaded-line	0.67 ± .09	1.32 ± .08	--
90.0	Reflection	0.50 ± .06	1.00 + .25	110**

* Includes 2 DC breaks @ 0.17dB/break.
** Was 101° prior to tuning

The measured performance data indicate an insertion loss of 4.52 dB at 35 GHz for the four-bit cascade (assuming 0.2 dB for an extra DC break). We estimate, however, by comparing the trends between measured and calculated performance that a true 180° bit might have a loss of 0.7 db above theoretical, indicating a four-bit insertion loss of 3.9 dB; only 1.6 dB higher than the predicted 2.3 dB It is reasonable to assume that this loss can be improved upon by using better quality diodes, smoother substrates (MIPP finish) and in particular by improving upon the design of the 90° hybrid. The phase errors are easily corrected by using diodes with a tighter capacitance specification and by small adjustments to the stub impedances.

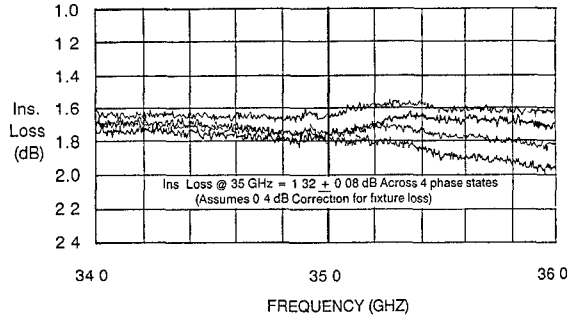

Figure 6. Measured Loss vs. Phase State of a 22 5°/45° Cascade

Power handling is limited by the 180° bit to an estimated 16.7 Watts.[3] However, if the circuit is configured with this bit at the end of a transmit chain, then assuming 2.5 dB loss from the remaining bits, the complete phase shifter can handle an estimated 29.5 Watts.

ELECTRONICALLY STEERED LINE ARRAY

A six-element space-fed active line array was assembled incorporating the above phase shifter with printed dipole radiating elements. The radiating element was microstrip-fed with an integral balun, fabricated on fused silica (Fig.7). A complete evaluation of this antenna is detailed in earlier papers.[4,5] Shown here are its measured E- and H- plane radiation patterns (Fig.8).

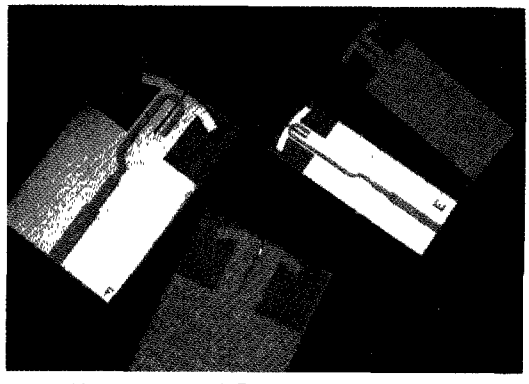

Figure 7. Ka and V-Band Dipole/Balun Radiating Elements on Fused Silica

A photograph of the complete assembly is shown in Figure 9. The radiating elements were printed 0.2 inch apart on a single fused silica substrate. Control bias is fed to each phase bit via a glass supported feed-through from a thin printed circuit board located on the underside of the assembly. The complete unit employs 138 bondwires, 14 substrates, and 60 PIN diodes and was successfully assembled with zero defects. The radiating elements were added without knowing the exact phase shifter characteristics (for which earlier work had suggested the 90° bit may not be ideal) due to

difficulties experienced with making non-destructive RF connections.

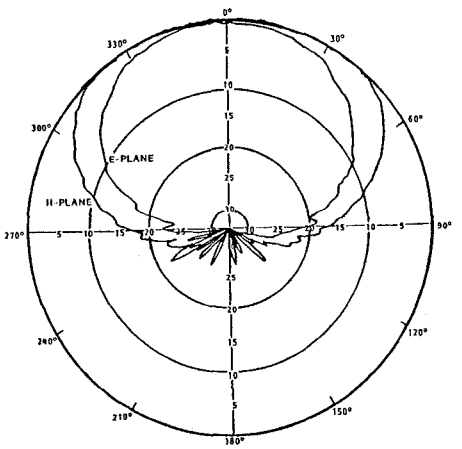

Figure 8. Measured E- and H- Plane Radiation Patterns of The Ka-Band Dipole/Balun

The complete unit was evaluated within our anechoic chamber test facility. Since each phase shifter could not be characterized some uncertainty existed in their zero state insertion phase. Therefore, the phase shifters were empirically set so as to yield the highest broadside signal level. The calculated phase gradients to effect beam scan to 15°, 30°, & 45° were then added to the broadside settings and at each beam position the phase states were toggled plus or minus a couple of bits to maximize signal level. The main lobes of the phase steered pattern are detailed in Figure 10. The measured sidelobe levels were typically -8 dB. A more accurate knowledge of the phase shifter states would allow a reduction of these sidelobes closer to the theoretical value of 14 dB for the nearly uniform element illumination.

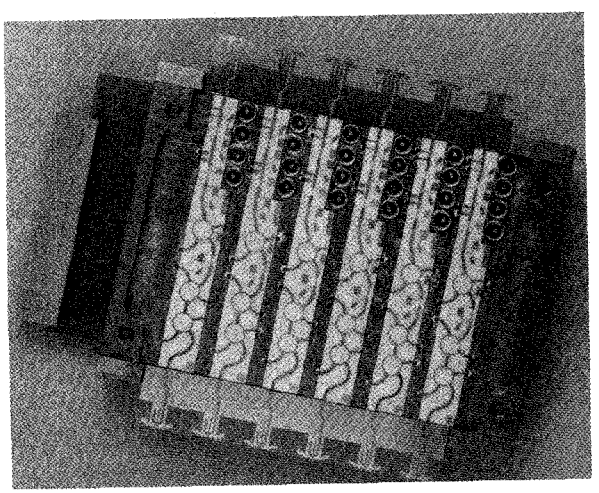

Figure 9. The Ka-Band Electronically Steered Line Array

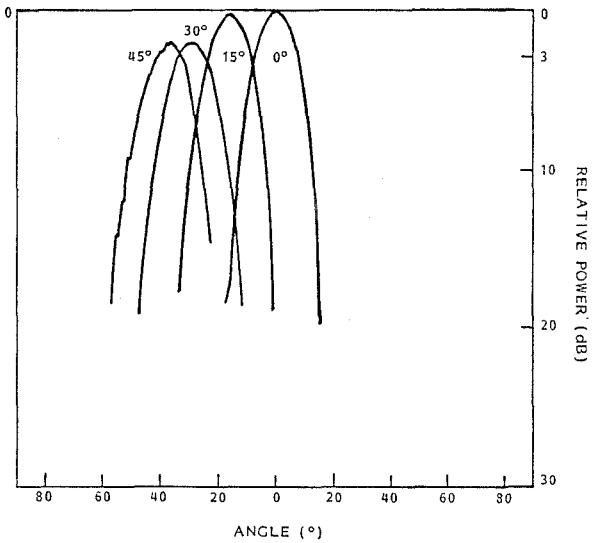

Figure 10. Measured E-Plane Radiation Patterns of The Ka-Band Line Array

CONCLUSION

A Ka-band electronically steered line array incorporating low-loss solid-state phase shifters and printed dipole radiating elements has been successfully demonstrated. The architecture is wholly compatible with monolithic technology and is therefore supportive of T/R modules with small size and low cost. We believe this work confirms the feasibility, at Ka-band, of a solid-state solution to an active phased array.

ACKNOWLEDGEMENTS

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