Composite Stripline Phase Shifter With Low Loss and Minimum Weight

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Abstract

An S-Band phase shifter is described using lightweight composite construction for low cost manufacture with batch processing. Couplers and phase shift networks are grouped together on an unusual printed air stripline medium. Lumped elements and critical ground paths are contained in a mass producible, individually testable hybrid circuit.

The low loss, lightweight phase shifter is readily integrable with distribution manifolding and printed radiator arrays.

NOVELTY AND APPLICATIONS

This paper describes a new approach to lightweight, low loss phase shifters which are readily integrated into printed distribution manifolds and array antennas.

Novelty centers on :

1.) Lightweight bonded honeycomb stripline which can economically reproduce large numbers of circuits by a "step and repeat" batch processing procedure.
2.) A efficient partitioning of the design such that all distributed elements use the ultra-low loss air stripline medium. All critical lumped elements and ground paths are contained in a "drop-in" hybrid circuit which can be mass produced and pre-tested before inclusion in the overall antenna circuitry.
3.) Perfection of overlay couplers in mixed-dielectric medium with compensation of the unequal odd and even mode velocities.

Applications are low cost, lightweight conformal arrays with minimal phase shifter losses.

1.0 BACKGROUND

Numerous phased array antennas have been built which are essentially passive, except for electrically adjustable phase shifters at each radiating element. The primary justification for this approach, as opposed to active T/R modules, is usually reduced cost, although there are sometimes other considerations such as weight, survivability, or thermal and electrical distribution.

The key to successful implementation of a passive array is the availability of low cost phase shifters which may be built at minimum loss. Phase shifter loss is especially critical because it is in the path of both the transmitter and receiver of a radar. In airborne or space applications, the phase shifter weight is also a critical design parameter. For example, one concept for an S-Band Space Based Radar is a very large aperture, 10's of thousands of elements, each with quite low transmit power of only a few watts. Such an approach is not desirable with active T/R modules due to the extremely high cost to 10's of thousands of active modules. Also, large numbers of very low power modules have a specific weight disadvantage, measured in grams per watt, as compared to centralized high power transmitters.

The phase shifter to be described in this paper addresses the specific need for minimum loss performance, with an architecture which is optimized for very low cost, light weight, mass production.

2.0 COMPOSITE STRIPLINE CONSTRUCTION

A PIN diode phase shifter has been designed using composite stripline construction, which is illustrated in Figure 1. The center conductors of the stripline are printed on a thin substrate which is suspended between two ground planes by low loss honeycomb dielectric material. Each of the elements of this "sandwich" is flimsy when examined by itself, but a strong lightweight structure results when the elements are bonded together with adhesive. The stripline which is formed by this technique is essentially air dielectric, which provides the lowest loss TEM medium available. The most critical tolerances are contained on the printed substrate and are readily handled by standard printed circuit processing. The relatively large dimensions of the ground plane spacing, typically about 0.15 inch, is not very sensitive to production tolerance variations of a few mils. Although air stripline circuitry is large compared to microstrip or MMIC techniques, it is mostly air and is very light weight per circuit. The very low loss of this medium is jointly due to the relatively large size of the conductors, and the virtual absence of dielectric losses.

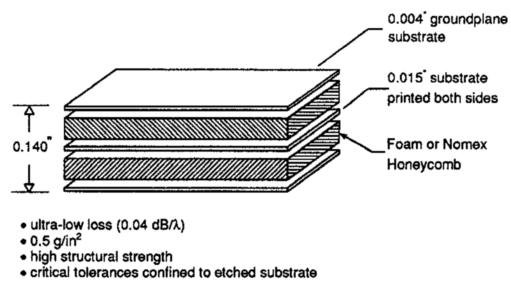

Figure 1. Composite Stripline Construction

Figure 2 shows a demonstration panel of phase shifters and printed circuit radiators formed by the bonded composite stripline technique. Note that it may be formed into curved surfaces for conformal applications. Since many circuits are manufactured together in a "batch" process, the cost per circuit is very low.

Figure 3 shows an implementation of the phase shifter in a low cost array architecture. For each row or column, losses and weight are minimized by integrating the distribution manifold and phase shifters without connectors. Low cost is obtained by batch processing of the array columns and the requirement for only a few relatively high power T/R modules.

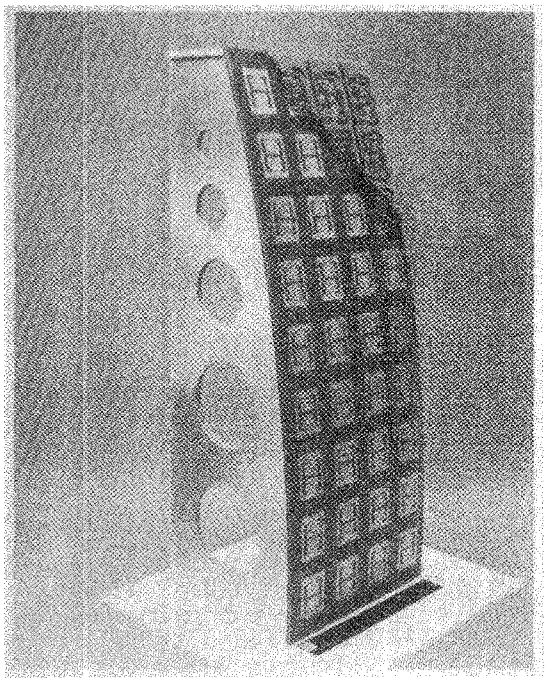

Figure 2. Printed Array of Phase Shifters and Radiating Elements

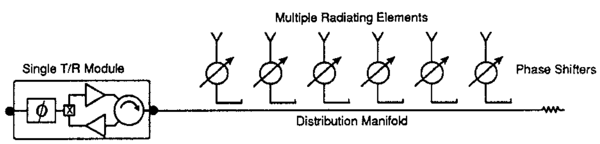

Figure 3. Low Cost Array Architecture

3.0 PHASE SHIFTER

The phase shifter design chosen for the 4-bit phase shifter is of the hybrid coupled reflective type [1], as shown in Figure 4. This approach was primarily chosen because its topology lends itself well to the suspended stripline construction. The entire RF circuit may be directly etched on the stripline substrate while the diodes and their bias circuits may be conveniently located outside the substrate.

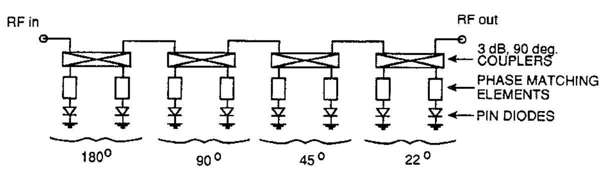

Figure 4. Hybrid Coupled Reflective Phase Shifter

Referring to Figure 4, a hybrid (3dB, 90 degree) coupler is used with equal reflective terminations at each of the coupler's two outputs. The reflected signals sum at the normally isolated port of the coupler, thus a transmission phase shifter is achieved. The phase of the transmission depends on the phase angle of the reflective terminations, and is switched from one state to another by switching the bias on each pair of diodes from forward to reverse. The amount of phase shift is, therefore, the difference between the phase angles of each of the states, and is determined by the reversed biased diode capacitance as well as the matching circuits between the coupler and the diodes.

4.0 COUPLER

A partially offset overlay coupler was developed for the phase shift bits to provide broadband, low loss performance [2]. Suspended substrate stripline was chosen as the best medium for low loss, lightweight construction. This configuration, shown in Figure 5, is a convenient and easily manufactured method of construction tightly coupled lines in stripline. The substrate is suspended between the ground planes by a low density Nomex honeycomb, which approaches the low loss available from air dielectric, while controlling the spacing between the coupled lines.

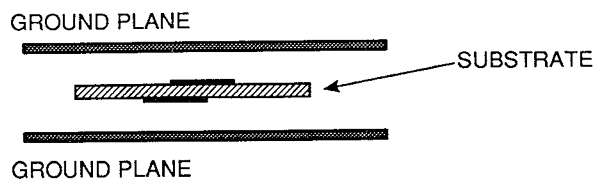

Figure 5. Partially Offset Overlay Coupler

Coupling values for the variable offset lines [3,4] were obtained by field mapping the geometry to determine the line capacitances under even and odd mode strip impedances. Design curves for 0.015 in PTFE substrate and 0.062 honeycomb have been calculated and are shown in Figure 6. The amount of overlap between the conductors is specified as "fractional overlap" as referred to the conductor width. The effective dielectric constants for the even and odd modes is also shown. This data was then analyzed and the coupler compensated using a microwave CAD program.

The mixed dielectric structure restricts bandwidth, directivity and impedance match due to the different wave velocities of the even and odd modes. In the even mode, very low fields exist in the dielectric between the strips, and wave propagation is relatively fast. In the odd mode, high fields occur in the substrate, and wave propagation is slowed. This effect is seen as a net inductive component at the coupler input and limits the match to about 20 dB.

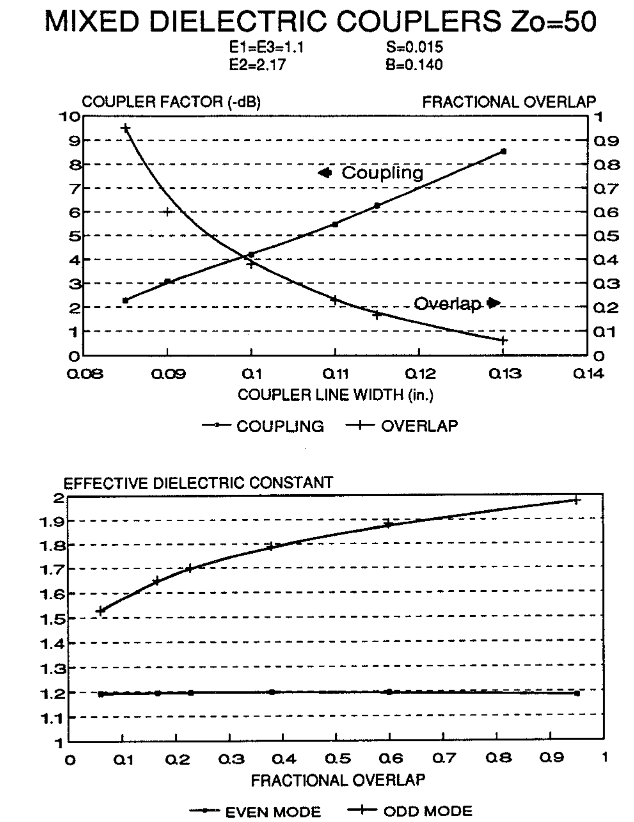

Figure 6. Coupler Design Data for S=0.015 and B=0.140

Coupler match and directivity are key to producing a low loss phase shifter because, as the couplers are cascaded, the net reflective mismatch is additive. Worst case interaction from cascading four uncompensated couplers would result in 9 dB return loss and, more importantly, .6 dB insertion loss. Similarly, for a 20 dB cascaded match, each coupler requires better than 30 dB input return loss. The coupler data was analyzed on Touchstone and the effect of the different mode velocities was tuned to an acceptable level. Capacitive stubs were added at the input and output, resulting in nearly 30 dB return loss across a 20% bandwidth. The measured coupler results show very good agreement with the predicted response, as shown in Figure 7.

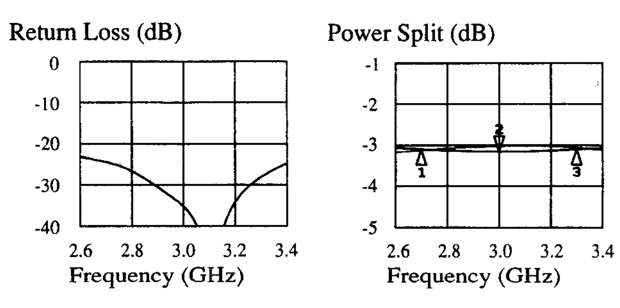

Figure 7. Measured Coupler Results

5.0 PIN DIODE HYBRID

All active devices and lumped elements used in the phase shifter were assembled in a miniature hybrid package. The hybrid approach provides three advantages, 1) it relegates all component attachment to the hybrid package off the stripline substrate 2) allows for pretesting of the critical components prior to assembly with the stripline and 3) contains all the critical RF grounding. The hybrid circuit schematic and diagram are shown in Figure 8.

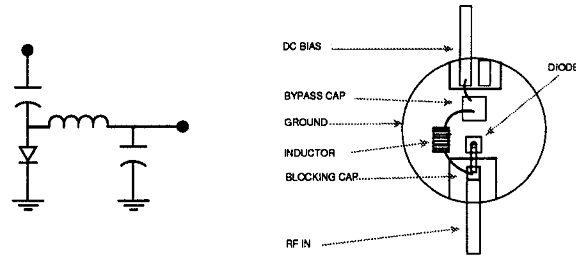

Figure 8. Hybrid Assembly Details

Computer modeling indicated that the diode should be located as close the the RF lead as possible. This minimizes transmission losses into the package and improves phase flatness. Areas critical for low loss include the launch into the package, the series blocking capacitor, the bond ribbon to the diode chip and the ground inductance. The diode itself was chosen for its phase shift parameters, minimum loss and low amplitude modulation [5]. The hybrid circuit was assembled on 25 mil alumina substrate with thick film copper metalization. The launch into the package is 50 ohms, allowing a 22 mil line width. The DC block is a 17 pF MIS capacitor chosen for high Q and small size. A 20 mil jumper ribbon was welded from the series capacitor to the diode. Test indicated an 0.15 dB loss improvement for the ribbon over a single 1 mil bond wire. The diode chip was soldered down for low contact resistance. The substrate metalization is edge plated for a low inductance wrap around ground. This assembly is covered with a hollowed out copper lid and a shim added to the bottom to meet the ground plane spacing for the suspended stripline circuitry.

6.0 PHASE SHIFT CIRCUIT TOPOLOGIES

The topology chosen for the phase shift circuit is a distributed equivalent of an L/C low pass network [6]. Alternate sections of short lengths of high impedance and low impedance transmission line sections are used to realize the L/C elements as stripline circuit elements. The distributed circuits are etched directly on the stripline substrate and are located between the hybrid couplers and the PIN diodes located at the edge of the stripline circuit. The PIN diodes and the bias circuit components are mounted in a separate hybrid package. By selecting the proper circuit element values, a flat phase response was achieved for the desired phase shift over a significant bandwidth [7]. Computer modeling was used to calculate the circuit elements necessary to achieve satisfactory phase shift characteristics over the required band.

The phase shifter was designed for optimum performance over a 20% frequency bandwidth. The performance was calculated for each phase shifter bit for several different available PIN diodes. In each case, the stripline circuit element values were optimized for minimum phase shift error, minimum insertion loss variation and minimum insertion loss over the 20% bandwidth. Optimum performance was achieved for each phase shifter bit with a different PIN diode. The diode parameters used for each bit are shown in Figure 9.

PHASE SHIFTER	Cj (pF)	Rs (ohm)	Rr (ohm)
180	.39	0.4	0.8
90	1.7	0.2	0.3
45	1.7	0.2	0.3
22.5	2.7	0.12	0.13

PHASE SHIFTER	MAXIMUM PHASE ERROR	MAXIMUM LOSS VARIATION	MAXIMUM INSERTION LOSS
180°	2.0°	0.02 dB	0.24 dB
90	1.0	0.02	0.26
45	0.8	0.04	0.25
22.5	0.8	0.03	0.16

Figure 9. Diode Parameters.

The performance of the 4 bit phase shifter was computed for each of the 16 phase states. The insertion averaged about 0.8 dB over most of the band with a variation of about 0.1 to 0.15 dB. At the high end of the design band, the computed insertion loss averaged about 0.9dB.

7.0 RESULTS

Figure 10 shows a composite phase shifter with the top ground plane removed, as well as half of the top layer of Nomex honeycomb. All lumped elements, diodes and bias components, are contained in the round hybrid packages. These packages will mount in round holes in an overall larger substrate containing arrays of phase shifters. Only the printed transmission lines on the top surface of the substrate are visible.

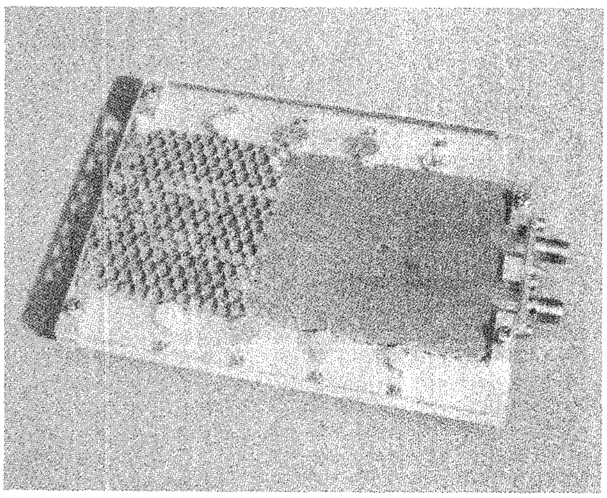

Figure 10. Prototype Composite 4-Bit Phase Shifter

Figure 11 shows the measured performance of the finished 4-bit phase shifter illustrated in Figure 10. Excellent performance was achieved over the 20% design bandwidth. The phase shift response of each of the four bits was adjusted to be within 2 degrees of its nominal value over the 20% band. The phase shift for all sixteen states is shown. The insertion loss measured about 0.9;0.1 dB over most of the band increasing to about 1.2;0.15 dB at the highest frequency. The increased loss at the high end of the band is largely due to the reduced return loss of the cascaded bits at high frequencies.

8.0 CONCLUSIONS

A phase shifter design and construction approach has been described which is unique in design approach, performance, and ability to be manufactured in large quantities by a batch process for low cost. The design approach capitalized on the optimal electrical properties of air stripline, with an electrical topology optimized for division of distributed passive circuitry and lumped, active elements. Overlay couplers and phase shift networks are grouped together on the printed air stripline medium. All critical lumped components and ground paths are contained in a mass producible, individually testable hybrid circuit.

Very low loss has been attained for a four bit, S-Band phase shifter which may be integrated with distribution manifolding and printed radiator arrays.

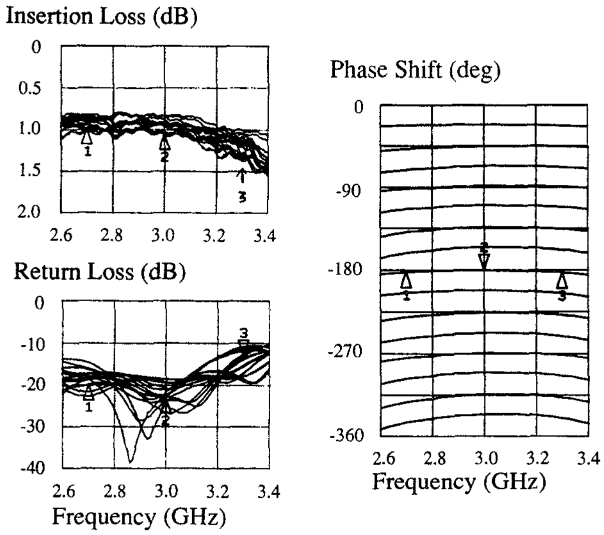

Figure 11. Measured Phase Shifter Performance

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