INTEGRATED 6-BIT PHOTONIC TRUE-TIME-DELAY UNIT FOR LIGHTWEIGHT 3–6 GHz RADAR BEAMFORMER

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ABSTRACT

Photonics will provide the interconnect solution for next-generation phased array radar antennas and satellite communications links, which have conformality, bandwidth, EMI immunity, size, and weight requirements increasingly difficult, if not impossible, to meet using conventional electrical interconnect methods. GE and AT&T aim to develop and implement fiber optic signal distribution networks that afford an octave of instantaneous bandwidth and that are 75 percent smaller and lighter than their electronic equivalents. We have developed a low-loss (nominally 14.0 ± 0.4 dB for λ=1.3 μm) integrated 6-bit photonic time-delay unit to be used in the demonstration of a photonic beamformer for eight subarrays of a 3–6 GHz phased array radar.

INTRODUCTION

In future-generation phased array radars, signal distribution methods will need to fulfill strict performance criteria. These include: greater than 60 dB isolation from both electromagnetic interference and crosstalk between module or subarray feeds; analog frequencies of operation into the millimeter-wave range with bandwidths of an octave or more; dramatic reduction in size and weight relative to present fielded radars; and less than 10 dB overall interconnect loss.

The metallic waveguides and coaxial cables currently used in radar phased array backplanes will be unable to meet these stringent requirements. Waveguides are heavy and bulky, and coaxial cables are highly susceptible to crosstalk between adjacent lines. Coax is also extremely lossy—an 18 GHz signal, for example, attenuates 1000 dB/km in a cable with a 1 mm outer diameter. Furthermore, as higher frequency phased array operation is pursued, element spacing will become increasingly tight, making waveguide congestion and crosstalk at the array backplane serious design concerns.

Optical fiber, on the other hand, is an ideal T/R module or subarray interconnect because it is very small—nominally 125 μm in diameter—resulting in less waveguide congestion at the array backplane. Glass fiber is rugged and flexible, with negligible weight, tensile strength greater than 10^6 lb/in^2, and minimum bend radius less than 1 inch. It is also virtually transparent to RF signals (attenuation is typically <0.5 dB/km), even at frequencies up to 100 GHz. Moreover, the replacement of a metallic waveguide system with a fiber optic network imparts immunity to interference (EMI and EMP) and typically >100 dB isolation from signal crosstalk.

These features make optical fiber the signal routing tool of choice for future phased array radars. Additionally, the transparency, small size and enormous bandwidth of the optical waveguide render it an attractive medium in which to perform true-time-delay phase shifting, because signals will incur the same loss in the shortest delay line as in the longest. It is this combination of benefits which has motivated us to develop the integrated photonic time-delay unit described in this paper.

SYSTEM ARCHITECTURE

GE and AT&T are jointly developing a 3–6 GHz low-loss photonic radar signal distribution system that performs true-time-delay beamforming in the optical domain. True-time delays permit greater bandwidth and hence higher-resolution phased array radar operation than what is possible using electronic phase shifters. Figure 1(a) is a block diagram of an electronic beamformer, and Figure 1(b) shows the

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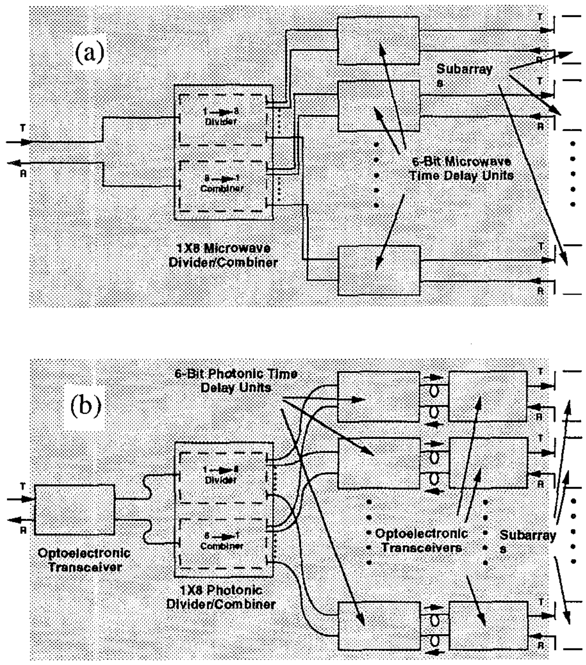

Figure 1

(a) Current architecture for electronic true-time-delay beamformer. Total mass=8000 kg.
(b) Proposed architecture for equivalent photonic true-time-delay beamformer. Total mass=2000 kg.

equivalent 3–6 GHz photonic architecture which will result in a 75 percent weight reduction.

Demonstration of the 3–6 GHz photonic beamformer depicted in Figure 1(b) requires the development of high-performance optoelectronic "building block" elements—the microwave/photonic transceiver, the 1×8 photonic divider/combiner, and the 6-bit photonic time-delay unit.

We presented the microwave/photonic transceiver design in June 1991 [1] and documented its performance in November 1991 [2]. The transceiver provides microwave-to-photonic as well as photonic-to-microwave conversion both at the I/O of the beamformer and at the beamformer-to-subarray interfaces. Connecting the optical input and output fibers of two transceivers creates a bidirectional fiber optic link (with 11 dB of microwave gain in its S and C passbands [2]) that replaces a coaxial cable.

The time-delay unit is the fundamental component in a wideband radar beamformer. In the proposed architecture (Figure 1(b)), each 6-bit photonic time-delay unit switches its assigned portion of the optical receive or transmit waveform into one of sixty-four fiber optic true-time delays in its package to steer the directional input/output of the T/R module array.

TIME-DELAY UNIT DESIGN

Figure 2 shows three different architectures we considered to realize six bits of bidirectional time-delay selectivity. The cascading of seven 2×2 switches is the simplest design, but in each path the signal incurs losses at fourteen integrated-optic waveguide/optical fiber interfaces. Using three 8×8 switch matrices minimizes the number of these waveguide/fiber transitions (six), but only with the addition of complexity and many unused ports (twelve).

Our approach was to design a bidirectional time-delay unit consisting of four 4×4 arrays of crossbar switches. This choice lent itself to a fairly straightforward integrated-optical waveguide and switch electrode layout, with eight waveguide/fiber transitions in each path—only two more than in the much more complex 8×8 switch matrix based architecture—and only four unused ports. The predicted overall optical insertion loss of 15 dB (for λ = 1.3 μm) is 3–4 dB less than what was expected if bidirectional 6-bit operation were sought using the seven cascaded 2×2 switches with fourteen waveguide/fiber interfaces.

Figure 3 shows the layout of sixteen crossbar switches in four cascaded 4×4 matrix configurations. The twelve fiber lengths used in the unit are also represented in this drawing to show how it offers sixty-four different total delays (0τ to 63τ). For our beamformer we desire a longest delay of ~30 ns, corresponding to $\tau \approx 470$ ps, or about 9.5 cm of fiber for the 1τ delay path.

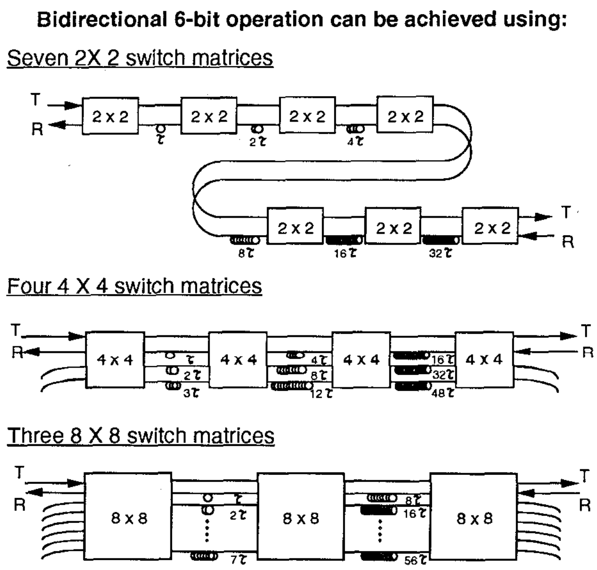

Figure 2

Alternative configurations employing integrated-optical switches and optical fiber delay lines to achieve 6-bit time-delay selection.

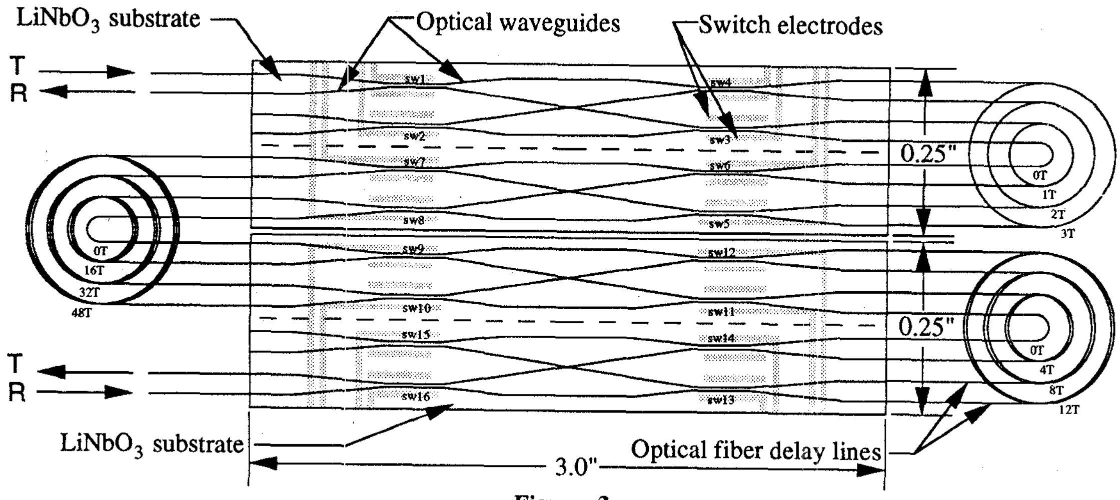

Figure 3

6–bit photonic time-delay unit design, showing the four 4x4 crossbar switch arrays realized using two 3-inch $LiNbO_3$ substrates.

TIME-DELAY UNIT FABRICATION

The four switch arrays were designed to fit on two 3-inch Z-cut $LiNbO_3$ substrates as shown in Figure 3. To create waveguides for the $\lambda = 1.3$ µm light, Ti was diffused to increase the refractive index of the $LiNbO_3$ in 6.5-µm wide strips. The directional coupler switches have a full-time reversed $\Delta\beta$ electrode configuration to allow each switch to be operated by a single driver. This structure has provided low-crosstalk devices with high yield [4]. The waveguide intersections were designed with angles greater than 8° to minimize both optical loss and crosstalk [5].

We used ALCOA-FUJICURA polarization-maintaining fiber for the delay lines to preserve the extinction ratio between the polarization-sensitive switches. To minimize the size of the unit without inducing microbending losses in the fibers, each of the twelve fiber delay lines was wound in a coil with a minimum diameter of 1.5 inches. The fiber ends were placed in etched silicon V-grooves, visually oriented by observing the stress rods, epoxied, and polished. The angular deviation of the fiber stress rod axis did not exceed ±1.5° from the normal to the axis defined by the array of fiber cores. These fiber-coil assemblies were then attached to the integrated-optic switch arrays using UV-curing adhesive.

Figure 4 shows the complete integrated photonic time-delay unit with four optical ports (transmit input and output; receive input and output), two $LiNbO_3$ substrates with a total of sixteen integrated optoelectronic switches, and twelve coiled fiber delay lengths, all of which fit into the 0.4"×1.5"×7.0" package.

TIME-DELAY UNIT PERFORMANCE

For each of the sixty-four optical paths through the delay unit we have measured the optical power at both output fibers when a known power was launched into one of the input fibers. Both the insertion loss and the extinction ratio (or port isolation) can be determined from these measurements.

An InGaAsP ($\lambda = 1.3$ µm) distributed-feedback laser diode and an InGaAs PIN photodiode, both with known responsivities and optical coupling efficiencies, were used for the input and output optical power measurements. A polarization controller in

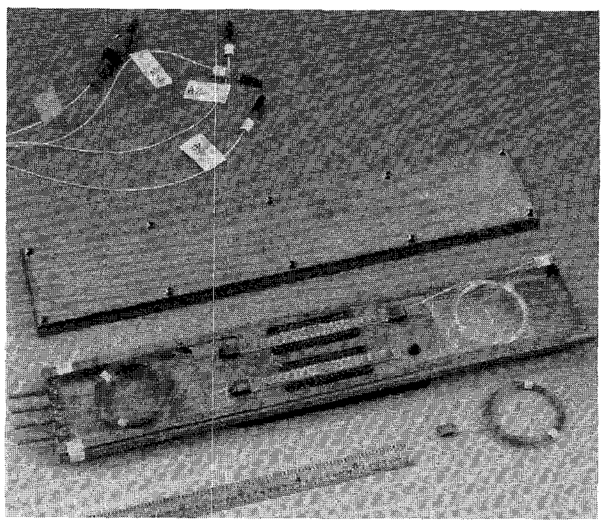

Figure 4

Bidirectional 6-bit time-delay unit. Overall size: 7.0"×1.5"×0.4" the link allowed adjustment of the optical field polarization at the input to the polarization-maintaining input pigtail of the time-delay unit. The launching of λ = 1.3 μm light that is linearly polarized parallel to the stress rods in the polarization-maintaining fiber results in optimum operation of the integrated-optical switches in the unit.

Table 1 shows the measured loss and extinction ratio for each of the sixty-four paths through the unit, along with the expected corresponding delay in nanoseconds. The total optical insertion loss (including one connection) exhibits a bimodal distribution. The majority of delays have total losses of 13.6 to 14.4 dB, and those paths which include the 32τ fiber delay loop (i.e., 32τ–47τ) have losses of 15.5 to 16.7 dB. The extinction ratio performance can be similarly grouped, with all paths without a 32τ delay exhibiting 20 dB or greater isolation. The delays that do include 32τ have extinction ratios ranging from 14.0 to 19.3 dB. The exact cause of the insertion loss and extinction ratio degradation in the 32τ fiber coil has yet to be determined.

Delay = __ x τ	Insertion Loss (dB)	Crosstalk (dB)	Expected Delay (x 10^{-9} s)	Delay = __ x τ	Insertion Loss (dB)	Crosstalk (dB)	Expected Delay (x 10^{-9} s)
0	14.0	23.0	0.00	32	15.8	18.5	15.04
1	14.1	26.0	0.47	33	15.7	18.8	15.51
2	14.1	26.5	0.94	34	15.7	19.0	15.98
3	13.8	26.3	1.41	35	15.6	19.1	16.45
4	14.2	22.4	1.88	36	16.0	18.3	16.92
5	14.4	22.5	2.35	37	15.6	18.3	17.39
6	14.0	22.7	2.82	38	15.5	19.3	17.86
7	13.9	23.2	3.29	39	15.5	17.2	18.33
8	13.7	25.0	3.76	40	15.5	17.7	18.80
9	13.8	25.0	4.23	41	15.5	17.6	19.27
10	13.8	25.5	4.70	42	16.2	14.5	19.74
11	13.8	24.2	5.17	43	15.9	16.2	20.21
12	14.2	23.5	5.64	44	16.2	16.2	20.68
13	14.1	24.6	6.11	45	15.5	17.9	21.15
14	13.9	24.6	6.58	46	16.3	14.0	21.62
15	13.6	24.6	7.05	47	16.7	15.5	22.09
16	14.4	21.2	7.52	48	14.1	22.5	22.56
17	14.4	21.4	7.99	49	14.1	22.1	23.03
18	14.3	20.4	8.46	50	14.1	23.8	23.50
19	14.1	22.3	8.93	51	14.3	22.5	23.97
20	14.2	21.9	9.40	52	13.9	21.4	24.44
21	14.2	20.9	9.87	53	14.1	20.0	24.91
22	14.2	20.8	10.34	54	14.3	21.2	25.38
23	14.0	23.0	10.81	55	14.1	21.0	25.85
24	13.8	22.5	11.28	56	13.7	23.4	26.32
25	13.8	22.4	11.75	57	13.8	22.9	26.79
26	13.9	22.6	12.22	58	13.8	23.3	27.26
27	13.8	22.8	12.69	59	13.8	22.2	27.73
28	14.0	22.0	13.16	60	14.0	21.5	28.20
29	14.1	21.5	13.63	61	14.0	21.1	28.67
30	14.0	22.0	14.10	62	13.8	22.2	29.14
31	14.0	22.3	14.57	63	13.8	22.5	29.61

Table 1

Results of the insertion loss and crosstalk measurements for each of sixty-four paths through the photonic time-delay unit.

A time-domain measurement to determine the true duration of each of the sixty-four delays is also being performed currently. Characterization of the delays is not an urgent matter, since any measurable discrepancy between the expected and measured delay durations could be corrected by changing one or more of the twelve fiber lengths in the package.

CONCLUSIONS

We have presented the design and measured performance of an integrated 6-bit photonic true-time-delay unit. Its construction will be modified slightly to decrease the variability witnessed in the extinction ratio measurements.

Two of the four "building block" elements of our proposed photonic beamformer have now been designed, built, and tested. By virtue of the optical fiber's small size, low loss, tremendous bandwidth capacity and immunity to EMI, the photonic beamformer will enable future development of smaller, lighter, higher-frequency, and higher-resolution phased array radars.

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