Guided-Wave Optical Time Delay Network

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***Abstract*— A hybrid optical time delay unit using lithium niobate switches and precisely produced fiber loops is described. Three prototypes of the device were fabricated and characterized. The measured optical extinction ratio between time slots is typically $\ll$25 dB. On average, delay values are within 0.7% of their design values. The device is a 6-b (64 time slot) delay unit with 44 picosecond per increment.**

I. INTRODUCTION

RAPIDLY reconfigurable optical time delay networks are essential components in a variety of applications. Optical signal processing systems require some form of variable, short term optical memory. Packet switching networks (such as ATM) require variable delays for queuing and packet retiming. In addition, radar beamformers based on optical time delays have previously been described [1], [2]. Availability of compact packaged devices will aid systems research in these areas.

In this letter, we report the second generation of a packaged 6-b optical time delay unit. Guided-wave directional coupler switches in lithium niobate provide rapid reconfiguration among the various fiber delay paths. Carefully produced fiber lengths supply the time delays in precise 44 ps time increments. The individual switch states are set according to a crosstalk avoidance algorithm that guarantees good extinction of the optical power at undesired delay times. The concepts described here can be combined with appropriate switch architectures and fiber lengths to provide a wide range of time delay functions.

II. DEVICE DESCRIPTION

The device layout is shown schematically in Fig. 1. The time delay unit consists of two lithium niobate die each of which has two 4 × 4 networks made of 4 directional coupler switches. These devices are designed to operate at 1.3 microns with TM polarization. The waveguide design and processing are similar to that described in [3] except that the directional coupler length is 20 mm. The substrate is 68 mm long and 6.25 mm wide. Each directional coupler is controlled by a pair of bias electrodes and a single switching electrode [3]. The bias electrodes can be tied together externally to minimize the number of required voltages or can be tuned separately to minimize switch element crosstalk.

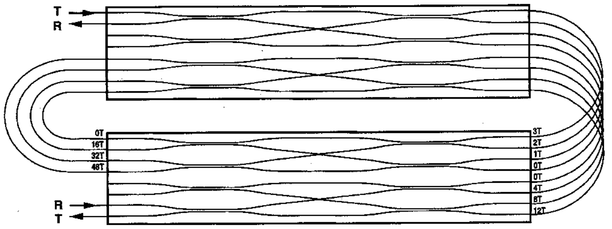

Fig. 1. Illustration showing the lithium niobate switches and the fiber loops. The numbers indicate the delay associated with each loop.

The four 4 × 4 switch element groups are interconnected by precisely manufactured lengths of polarization maintaining fiber that provide delays in multiples of 44 ps. The two dice and the twelve fiber loops (in two array pairs) are housed in a single package that provides physical protection and electrical and optical feedthroughs. The fiber lengths are controlled to be within ±0.75 mm of their nominal value. The technique for aligning the polarization maintaining fibers in the v-grooves has been described previously [3], [4]. The two pairs of arrays are fabricated, looped, and tested for length and polarization extinction ratio before being attached to the devices. A thin film polarizer is included inside the package to insure good polarization extinction ratio. The endfaces of each die are anti-reflection coated to suppress the interface reflection to <-25 dB. The four input/output fibers are terminated with keyed PMF connectors. Fig. 2 is a photograph of a completed device. The die are bonded to two separate pedestals. Wire bonds are made between the package pins and the 24 bond pads on each substrate. The coiled delay fiber is held loosely around two spools. The four input/output fibers pass through one end wall of the package.

To assure large extinction ratios between delay paths, a "crosstalk avoidance" algorithm is used when a given delay path is set up. Establishing a desired delay path dictates the states of eight of the fourteen switch elements in the time delay unit. Crosstalk generated at each of these switches continues to propagate through the device and can potentially couple back into the main signal path at a subsequent switch. This "crosstalk signal" will have travelled through a different series of fibers and will have a different delay time thus causing a increase in extinction ratio at the output of the device. Since this light can only couple back into the signal path due to the imperfections of a switch set to reject it, its power level will be down by twice the crosstalk value (in dB) for one of the switches. This level can be reduced further by using the

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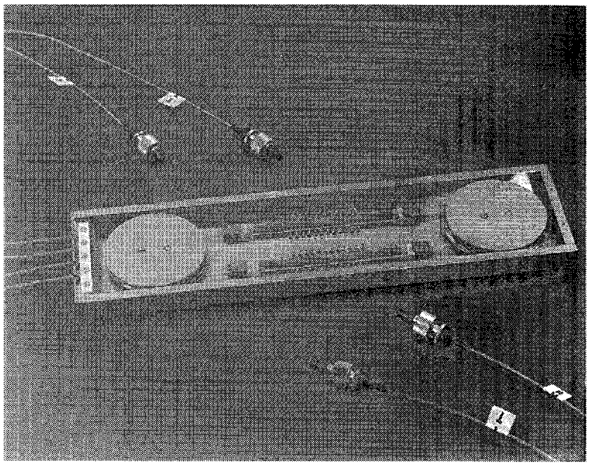

Fig. 2. Photograph of the finished device.

TABLE I
SUMMARY OF PERFORMANCE CHARACTERISTICS OF EACH OF THE DEVICES

	Device 1	Device 2	Device 3
Mean insertion loss (dB)	-15.8	-16.9	-14.9
Insertion loss standard deviation (dB)	±0.4	±0.4	±0.8
Insertion loss range (dB)	-15.0/-16.7	-16.2/-18.1	-14.0/-16.8
Mean bias voltage (V)	-3.15	-3.15	-3.15
Mean switching voltage (V)	3.75	3.75	3.5
Mean time delay error (ps)	0.22%	0.53%	0.69%
Maximum time delay error (ps)	9.1	11.3	14.0

TABLE II
SUMMARY OF THE DELAY TIMES FOR EACH OF THE FIBER LOOPS

	Design	Device 1	Device 2	Device 3
1τ (ps)	44	44.1 ± 0.2	44.6 ± 0.5	42.5 ± 0.3
2τ (ps)	88	87.0 ± 0.6	86.6 ± 0.7	85.2 ± 0.5
3τ (ps)	132	132.3 ± 0.5	130.9 ± 0.7	128.4 ± 0.5
4τ (ps)	176	175.6 ± 0.3	173.0 ± 0.4	175.4 ± 0.3
8τ (ps)	352	351.4 ± 0.4	349.3 ± 0.6	350.9 ± 0.5
12τ (ps)	528	525.8 ± 0.4	525.0 ± 0.6	526.9 ± 0.5
16τ (ps)	704	704.0 ± 0.4	701.4 ± 0.3	700.0 ± 0.4
32τ (ps)	1408	1404.3 ± 0.8	1403.1 ± 0.8	1402.8 ± 0.7
48τ (ps)	2112	2106.1 ± 0.9	2105.1 ± 0.8	2102.7 ± 0.7

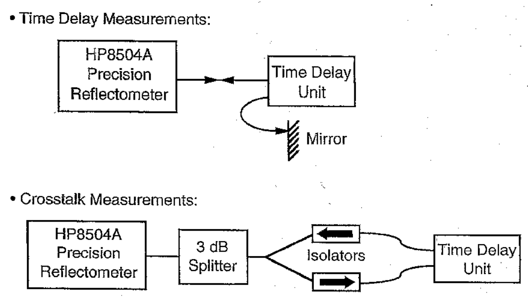

Fig. 3. Apparatus for time delay and extinction ratio measurements.

remaining six switches to route crosstalk light generated at some switches to the unused ports at the output of the device. By choosing the switch states of the six switches that are not required for the main path, extinction ratios for these paths can be three times lower (in dB) than the crosstalk for the individual switches. For instance, by properly setting switches that are not required for the signal, crosstalk from the first switch can be routed through the network in a path parallel to the signal.

III. MEASUREMENT TECHNIQUES AND RESULTS

Three devices were fabricated, packaged and tested. The packaged dice were taken from three different wafers. The devices were thoroughly characterized for insertion loss, bias and switch voltages, time delay values and the extinction ratio of the power in the desired delay path to each of the other delay paths.

The data is summarized in Tables I and II. The mean insertion loss (including four fiber-waveguide-fiber coupling losses) varies from -14.9 to -15.9 dB. The primary source of this variation is associated with attachment of the polarizer chip. For the third device, the attachment process was modified to improve parallelism between the chip and the device endface. The modification resulted in a lower insertion loss. The value reported in Table I for this device includes higher loss in several delay paths associated with one of the fiber loops. Without these sixteen paths the mean insertion loss is -14.3 dB with a range of ± 0.4 dB.

Before packaging, each directional coupler on each die was characterized to determine the set of voltages (two separate bias and one switching) which produced the lowest crosstalk (typically <-25 dB). In addition, the voltage for minimum crosstalk with the bias electrodes tied together was also determined. For this case, crosstalk was in the range of -10 to -25 dB for voltages that varied from switch to switch by ± 0.35 V about their mean. The combination of uniform voltages, low crosstalk and the crosstalk avoidance algorithm makes it possible to simplify system operation and control all three devices with a single value for V_{bias} (-3.15 V) and V_{switch}(3.75 V).

An HP 8504A precision reflectometer was used for the time delay and extinction ratio measurements. As shown in Fig. 3, the time delays (relative to the zero delay path) were measured by using a mirror to reflect the light from an output fiber back through the device. Since the total delay time exceeded the span of the reflectometer, several different fiber lengths were used in the reference arm. The mirror technique was inappropriate for crosstalk measurements because spurious crosstalk appeared on the return path through the device. The crosstalk avoidance algorithm (see previous discussion) only assures low crosstalk for light travelling forward through the device. For light travelling in the reverse direction, crosstalk light that is only two levels down can couple back into the main signal path and result in apparent crosstalk results that are worse than those expected in actual applications. To avoid this problem, the experimental setup shown in the lower part of Fig. 3 was used. The 3-dB splitter and the two isolators allow light to be returned to the reflectometer without passing twice through the device. Thus the network crosstalk can be characterized in a system-like configuration.

Each of the 4032 extinction ratio terms for each time delay network was measured with the mean voltage values applied to the switches. 98% are below the measurement noise floor of −25 dB. Only 8 terms have extinction ratios in excess of −20 dB and no term is greater than −15 dB.

If necessary, the extinction ratios could be improved by using the optimized control voltages for each switch. This may be necessary for systems in which use of a narrow line laser can lead to coherent crosstalk effects (5). The crosstalk reduction algorithm discussed above routes crosstalk that is generated in the first 2 × 2 on each die away from the signal path. However, crosstalk generated in the second column of switches on a die can couple back onto the signal path at the first column of switches on the next die (see Fig. 1). With a DFB laser, we observed ±0.7 dB intensity fluctuations when the mean voltage values were used. Use of the optimized voltages reduced this intensity noise to ±0.1 dB.

The device was designed for time delays ranging from 0–2.772 ns in 44-ps increments. Fig. 4 shows the percent delay error for each of the 64 time delays for one of the devices. The small mean error (0.22%) attests to the precise fiber length control. The mean cumulative offset in the time delay through the three fiber loops is 3.3 ps and the maximum is 9.1 ps. Data for the other devices is given is Table I. Table II lists data for the time delay accuracy achieved in each fiber loop for each device. These values are derived statistically from the measured total time delays. The average of the ratio of the derived value to the design value is 0.993. The average of this ratio for the longer loops is 0.996. The systematic error in delay times indicates a systematic error in the fiber loop fabrication that appears to have resulted from a 0.4% underestimation of the fiber's group index.

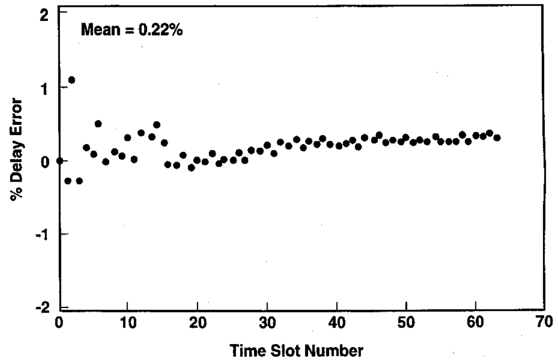

Fig. 4. Plot of the percentage time delay error versus time slot number.

IV. SUMMARY

In summary, we have designed and built a high-performance optical time delay switch that has potential applications in optical signal processing and switching.

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