Pseudo-analog true-time-delay module based on substrate-guided wave and WDM

Future generations of satellites, aircraft, missiles, ships, and wireless communication systems will require antennae and radar with strict performance requirements. The use of photonics, phased array, and true-time-delay (TTD) technology opens the possibility of high performance antenna systems while meeting stringent weight and size requirements.[1,2] Various types of photonic TTD units have been demonstrated by different research groups.

In our approach, 2-D substrate-guided wave and wavelength-multiplexing technology are employed to achieve TTD devices with a very high packing density and continuously tunable delays. The system structure is shown in Figure 1. A 1-to-N fiber beamsplitter, with pre-determined output fiber lengths, is used to provide N delayed signals, each with a delay increment of M. The input holographic grating coupler is designed to couple the surface-normal incoming light into a substrate guided mode. The output holographic grating couplers extract an array of substrate-guided beams into a free-space one-dimensional (1-D) array with M surface-normal fanout beams. Equivalent delay intervals are obtained at subsequent fanouts due to an equivalent propagating delay.

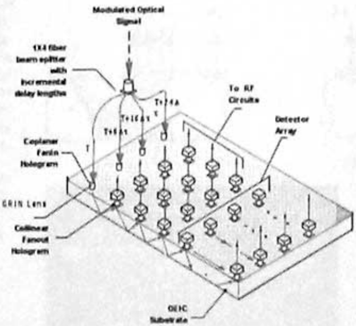

Figure 1. Structure of substrate-guided-wave true-time-delay lines.

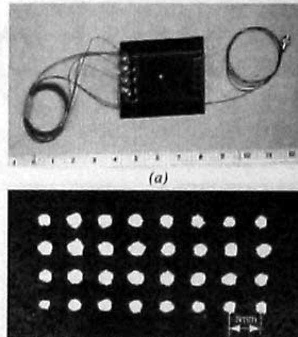

Figure 2. a) Packaged 5-bit TTD module. b) Fanouts of the 5bit TTD modules.

The time delay between two successive colinear fanouts is $\Delta\tau$. Thus, M·N delay lines are achieved. Based on this structure, up to 7-bit true-time-delay lines have been demonstrated with delay steps of from 15 ps to 100 ps.[3] The highest packing density achieved is 10 lines/cm^2. A 5-bit device is shown in Figure 2 together with its 32 fanouts. The bandwidth of such a packaged 5-bit device is measured to be 2.4 THz and the fanout beam uniformity is within ±10%. For an N-bit device, the total insertion loss from the input to each individual output is about 3N+2 dB. However, the total energy loss from input to all output signals is less than 2 dB. The working wavelength of the devices is around 1550 nm, which makes it easy to amplify the optical signals using commercially available Erbium-doped fiber amplifiers.

The fanout optical signals can either be detected by a high-speed photodetector array and then sent to antenna transmitters by programmed switching, or can be switched and amplified in the optical domain and then sent to the detector behind each antenna transmitter. Since all delay signals can be achieved simultaneously using one delay unit, a single unit can be used to control the whole antenna array. To scan into one direction, a set of discrete delay signals is selected to feed the antenna elements. To scan to another angle, another set of discrete delay signals is selected from all the fanout-delay signals to feed the antenna elements.

Due to the dispersion of the holographic volume grating coupler, the angular deviation of the diffraction angle θ of the surface-normal grating coupler, with respect to perfect phase-matching diffraction angle, can be written as[4] $\Delta\theta = \Delta\lambda \cdot \tan\theta/\lambda$. Therefore, if the wavelength of the beam incident to the coupling in hologram changes slightly, the corresponding diffraction angle within the substrate will follow this change as shown in Figure 3a). As a result, the length of the optical delay path after n times of bounces will be changed slightly, which results in a small perturbation of the signal delay. Figure 3b) and 3c) show the 8 different incident wavelengths and the corresponding fanouts after 8 bounces. Therefore, the delay step can be continuously tuned by tuning the working wavelength. By employing a tunable laser source and highly dispersive output fiber that has the same dispersion characteristics as that of the substrate guide wave device, continuous delay tuning around M·N discrete delay signals can be achieved.[5] Therefore, once the configuration of the delay signals is set to steer the beam into one discrete direction under one wavelength, continuous scanning in a small neighborhood around the designated direction can be achieved. This

continued on p. 10

SPIE Society of Photo-Optical Instrumentation Engineers

P.O. Box 10 • Bellingham, WA 98227-0010 USA

Change Service Requested

DATED MATERIAL

Non-Profit Org.
U.S. Postage Paid
Society of
Photo-Optical
Instrumentation
Engineers

00533478 OPC10-1
MR. ZHENHAI FU
UNIV OF TEXAS
PRC-MER 1.606-R9900
MICROELECTRONICS RESEARCH CTR
AUSTIN, TX 78758

Photonic processing

continued from p. 8

nel, a laser beam is modulated at frequency f_i or f_{LO}. Phase differences equivalent to 10 ps delays at f_i = 700 MHz were measured, permitting in-phase addition of the received signals (received signals were generated using time delays that simulate reflection from the target). In addition, note that these systems could greatly benefit from a holographic backplane[2] to make them more compact, more reliable, and for scaling up to 10^3 transmit/receive modules.

The authors would like to thank the DGA/STTC for partial support. P. Richin, D. Mongardien, J. Chazelas, G. Granger, T. Merlet and O. Maas (Thomson-CSF) are acknowledged for their contributions.

D. Dolfi, S. Tonda-Goldstein, and J.P. Huignard
Thomson-CSF
Laboratoire Central de Recherches
F-91404 Orsay Cedex
E-mail: dolfi@lcr.thomson.fr

References
1. N. A. Riza Ed, *Photonic control systems for phased-array antennas*, **SPIE Milestone Series MS136**, 1997.
2. D. Dolfi *et al*, **Appl. Opt. 35**, p. 5293, 1996.
3. S. Tonda-Goldstein *et al*, **IEEE/LEOS Topical Meeting Microwave Photonics TuB6**, p. 151, 1998.
4. L. Pastur *et al*, **Applied Optics** (accepted for publication).

Photorefractive-based

continued from p. 5

Engineering
University of Colorado
Boulder CO 80309-0525

1. Phone: 303/492-4661
Fax: 303/492-3674
E-mail: kelvin@colorado.edu
URL: http://optics.colorado.edu/MURI

2. Optoelectronic Data Systems
San Jose, California

References
1. K. Wagner, S. Kraut, L. Griffiths, S. Weaver, R. Weverka, and A. Sarto, *Efficient true-time-delay adaptive array processing*, **Proc. SPIE 2845**, 1996.
2. A. Sarto, K. Wagner, R. Weverka, S. Weaver, and E. Walge, *Wide angular aperture holograms in photorefractive crystals by the use of orthogonally polarized write and read beams*, **Applied Optics 29** (35), pp. 5765-5775, 1996.
3. T. Merlet, D. Dolfi, and J. Huignard, *A traveling fringes photodetector for microwave signals*, **IEEE J. of Quantum Electronics 32** (5), May 1996.

Pseudo-analog true-time-delay module

continued from p. 12

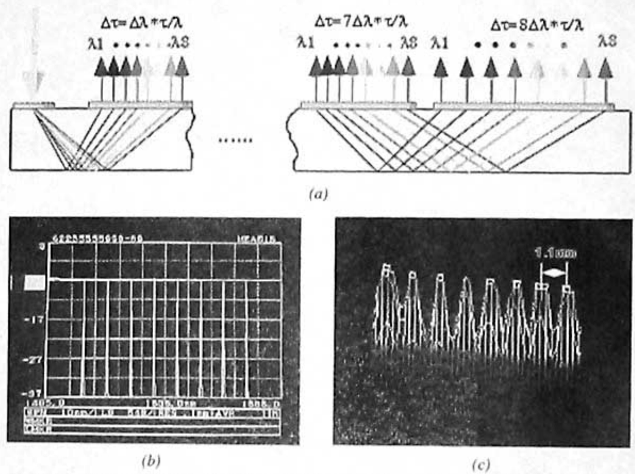

Figure 3. a) Structure of the wavelength-division-multiplexed TTD unit. b) Spectrum of the 8 incident wavelengths. c) Fanouts of different incident wavelengths after 8 bounces.

is done by continuously tuning the working wavelength to provide an continuously-tuned delay step.

In summary, substrate-guided-wave true-time-delay modules, which can provide up to 128 delay signals simultaneously under one wavelength and control the steering of a whole antenna array, are proposed and fabricated. By employing a continuously-tunable laser source and taking advantages of the dispersion of the holographic grating coupler, wavelength-division-multiplexed pseudo-analog true-time-delay lines can be achieved to continuously steer the radiated beam from phased-array antennae.

This research is currently supported by ONR, DARPA, AFOSR, BMDO, 3M Foundation, and the ATP program of the State of Texas.

Zhenhai Fu and Ray T. Chen
Microelectronics Research Center
The University of Texas, Austin, TX 78758
Phone: 512/4717035
Fax: 512/481-8575
E-mail: raychen@uts.cc.utexas.edu

References
1. A. A. Oliner and G. H. Knittel, **Phased Array Antennas**, Artech House, Dedham, 1972.
2. H. Zmuda and E. N. Toughlian, **Photonic Aspect of Modern Radar**, Artech House, Boston, 1994.
3. Z. Fu and R. T. Chen, *5-bit substrate guided wave true-time delay module working at 2.4THz with packing density of 2.5 lines/cm² for phased array antenna applications*, **Opt. Eng. 37** (6), p1838, 1998.
4. C. Zhou, Z. Fu, R. Chen, and B. Davies, *Dispersion correction of surface-normal optical interconnection using two compensated holograms*, **App. Phys. Lett. 72** (25), p. 3249, 1998.
5. Z. Fu, C. Zhou, and R. Chen, *Waveguide-hologram-based wavelengthmultiplexed pseudo-analog true-time delay module for wideband phased array antennas*, **Applied Optics** (will be published in May, 1999).