Radiant Research, Inc.

Suite 105
3006 Longhorn Blvd.
Austin, Texas 78758-7631
Phone: (512) 339-0500
Fax: (512) 339-1311
Web: www.radiantr.com

Phase I Final Report

Ultra Long Compact Polymer-Based Waveguide Circuit for Multi-link Optical True-Time-Delay Lines Using WDM Technique

Contract No.: F49620-98-C-0037

BMDO 98-003B (SBIR) **Topic Title: Sensors**

September 30, 1999

Technical Point of Contact:

Dr. Suning Tang
Principal Investigator and Chief Scientist

Phone: 512-339-0500-202
Fax: 512-339-1311
Email: suning@mail.utexas.edu

Professor Ray T. Chen
Technical Consultant

Phone: 512-471-7035
Fax: 512-471-8575
Email: raychen@uts.cc.utexas.edu

Contractual Point of Contact:

Mr. Fred Patterson
Vice President

Phone: 512-339-0500-201
Fax: 512-339-1311

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-99-

0266

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE 30 September 1999	3. REPORT TYPE AND DATES COVERED FINAL REPORT 1 AUG 1998 – 30 SEP 1999

4. TITLE AND SUBTITLE Ultra-long Compact Polymer-Based Waveguide Circuits for Multi Optical True-Time-Delay Lines Using WDM Techniques	5. FUNDING NUMBERS C F49620-98-C-0037
6. AUTHORS Dr. Suning Tang, Dr. Ray T. Chen	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Radiant Research, Inc. 3006 Longhorn Blvd, Suite 105 Austin, TX 78758-7613	8. PERFORMING ORGANIZATION REPORT NUMBER FR-9808
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research (Monitor) 801 North Randolph St, Room 732 Arlington, VA 22203-1977	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES Sponsored by BMDO/TOI/SBIR; 1725 Jefferson Davis Hwy, Suite 809; Arlington, VA 22202	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Statement A. Approved for public release; distribution is unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The optical true-time-delay line is a crucial building block for future photonic phased array antennas. In this research program, we have developed an integrated optical true-time-delay module based on ultra low-loss polymeric waveguides that have many advantages over existing approaches. The photolithography defined polymeric waveguides enable us to fabricate a 10-meter long optical channel waveguide circuit with sub-micron accuracy in a five-inch silicon wafer, providing optical true-time-delays over tens of nanoseconds with sub-picosecond time resolution. The unique detector-switched operation achieves a nanosecond switching time over 60 GHz bandwidth. Optical heterodyne technique is developed to generate optical RF signal in the range from 0-60 GHz. The demonstrated optical waveguide true-time-delay module employs wavelength-division-multiplexing technique for multi-beam operation. The monolithic integration of the polymeric channel waveguides, waveguide grating couplers, and highOspeed photodetectors drastically reduces the system payload and the packaging complexity while improving the system reliability. Through the Phase I research, we have successfully demonstrated the feasibility of the propos ed concept by realizing an integrated optical true-time-delay module based on ultra low-loss polymeric waveguide circuits.

14. SUBJECT TERMS Optical True-Time-Delay, Phased Array Antenna, Polymeric Waveguide, Integrated Optical Waveguide, Waveguide Coupler, High-speed photodetectors			15. NUMBER OF PAGES 37 16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

TABLE OF CONTENTS

1.0 IDENTIFICATION OF THE PROBLEM AND THE OPPORTUNITY

Phased Array antennas (PAAs) have attracted increasingly amount of attention and research efforts due to the proliferation of wireless and satellite-to-satellite communications [1-6]. Such antennas achieve beam steering through electronic phasing of each individual antenna elements [4], thus provide high speed scanning capabilities without mechanical steering and bulky payload. However the conventional phase shifting technique has performed at the microwave level and still requires large payload for variable phase shifters, power dividers, and other microwave circuits. Another drawback of the conventional approach lies in its narrow bandwidth and frequency dependent beam steering. To meet the large bandwidth needs of future PAAs, a time-delayed beam forming and steering technology in the optical domain must be implemented for frequency independent and widebnad operation [5-6].

The existing photonic PAA technologies with optical phasing include dispersive fiber delay [4], fiber grating prism [7], and optically switched silica-based waveguide circuit [8]. Those approaches have demonstrated promising performance characteristics over conventional approaches. Figure 1(a) illustrates the schematic diagram for a phased array antenna employing optical true-time-delays. The optical true-time-delays can be realized by the aforementioned three approaches. The fiber grating and optical switching approaches have been illustrated in Figure 1(b) and 1(c). In fiber Bragg grating technology, high performance reflection grating can be easily fabricated in ultra low-loss optical fibers, but very expensive fast wavelength tunable laser diodes have to be employed. The optically switched silica-based waveguide circuit offers excellent delay time control in a compact structure where the length of waveguide is defined by photolithography. However, the thermo-optical 2x2 switch as a key building block for this approach does not provide the switching speed and optical extinction ratio required.

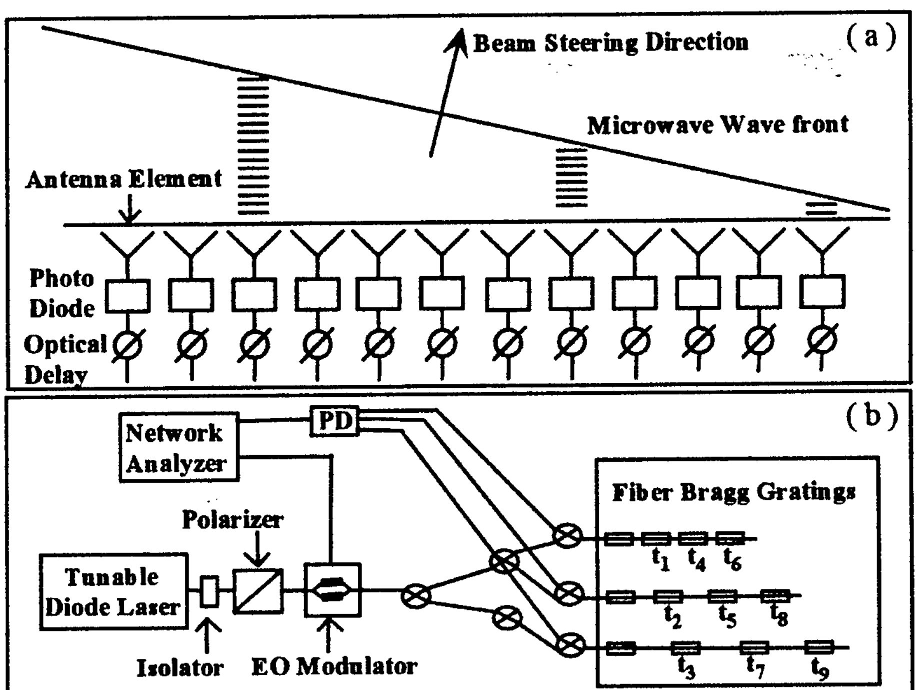


Figure 1. (a) Phased array antenna using optical true-time-delay. (b) Optical true-time-delay through Fiber Bragg Gratings in conjunction with tunable laser diode;

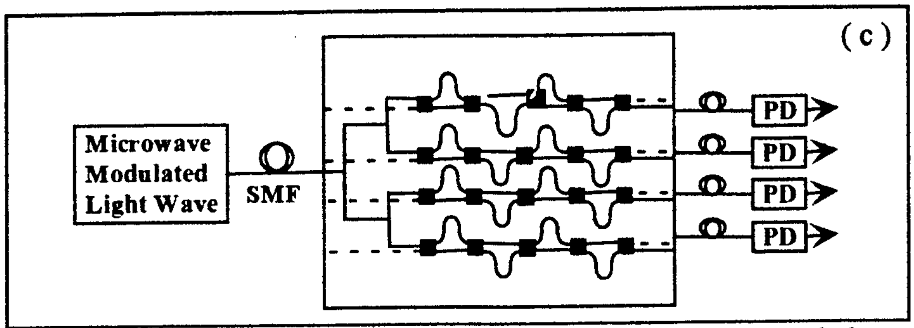


Figure 1(c). Optical delay through optical glass waveguide circuits and thermo-optic waveguide switch matrix.

BMDO has a need for frequency independent multi-link phased array antennas for broadband and high-speed links between communication satellites and ballistic missiles and/or air-vehicles so that communications can be maintained without lapse when such carriers are flying out of sight of one particular satellite. For such operation, the aforementioned PAA technologies present some severe problems. Firstly they cannot simultaneously provide multiple communication links due to frequency dependent operation. Secondly, they cannot provide high-speed beam steering due to the speed limitations of wavelength tunable laser diode and the 2x2 thermo-optic switches. Future phased array antennas should have an increased bandwidth (10 GHz to 40 GHz), improved range and cross-range resolution, capability of providing multiple links simultaneously at a reduced cost, weight and power consumption. As a result, an optical true-time-delay (TTD) technique with multi-link capability must be invoked for advanced airborne and space-borne applications.

1.1 Innovativeness and Originality of the Proposed Research

In this Phase I research program, we have proposed a drastically new detector-switched optical true-time-delay (TTD) line based on ultra-low-loss polymeric waveguide circuits as shown in Fig. 2, which is capable of providing true-time-delays from 1 ps to 50 ns for wideband phased-array antenna systems with multiple communication links. The proposed optical true-time-delay module produces an innovative and compact miniaturized TTD system by taking advantage of our capability in fabricating an ultra long and ultra-low-loss polymeric channel waveguide, an array of surface-normal fanout gratings, and an inexpensive monolithically integrated photodetector array. Using polymeric waveguide for optical true-time-delay reduces system payload, makes it possible to achieve surface fan out in a non-blocking structure. Due to the unique wavelength selective characteristics of waveguide grating couplers, multiple optical true-time-delays for multiple simultaneous communication links are simply provided by employing several directly modulated laser diodes in the same waveguide delay line based on the wavelength-division-multiplexing (WDM) technique. The application of the WDM technique makes the formation of a multi-link phased array an easy task without increasing the payload of an airborne or a space-borne platform. Unlike any conventional approach where one TTD line can provide only one delay signal at a time, the proposed module is capable of generating all required optical true-time-delay signals simultaneously to all antenna elements. In other words, a large number of true-time-delay combinations can be provided to the phased-array antenna simultaneously by electronic switching the photodetector array that is monolithically integrated with the polymeric waveguide in a same substrate as shown in Fig. 2. Such a monolithic integration not only reduces the cost associated with optoelectronic packaging, but also reduces the system payload with an improved reliability.

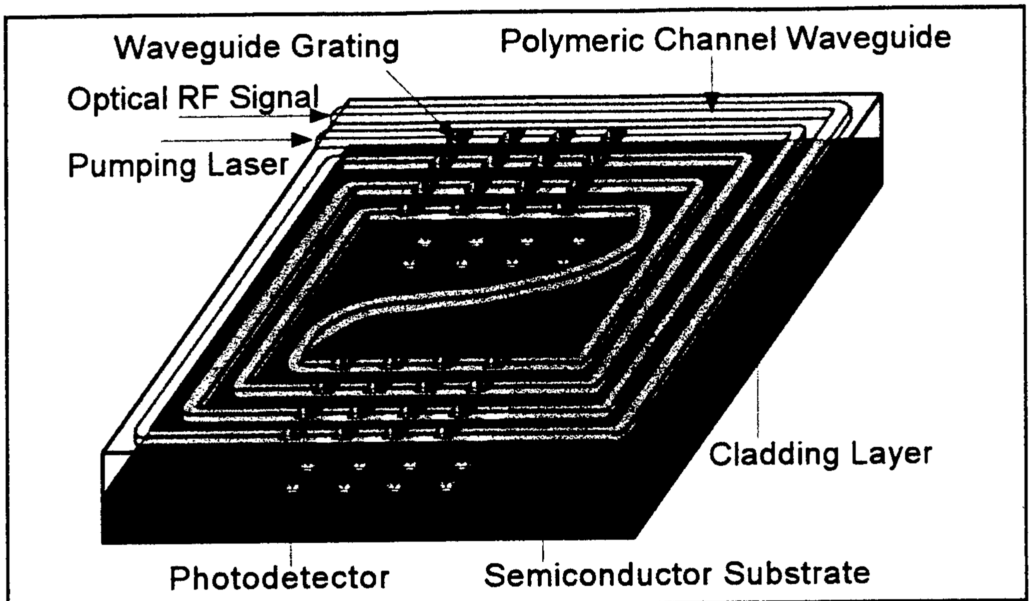


Figure 2. Schematic diagram of the proposed compact multi-link optical true-time-delay line based on an ultra-low-loss waveguide.

The innovative ultra-low-loss and low-dispersion polymeric waveguides in conjunction with waveguide grating couplers serve as an excellent optical medium for producing long optical delay lines for ultra wide bandwidth (100 GHz) operation. Its unique thin-film nature allows us to fabricate an integrated optical true-time-delay module (including high-speed photodetectors and waveguide circuits) on semiconductor substrate, using standard VLSI technologies originally developed in silicon industries. A large number of optical fanouts can be easily obtained over an ultra-long optical channel waveguide circuit by using surface-normal waveguide grating couplers [9-12]. Furthermore, polymeric waveguide amplifier (based on rare-earth-ions doped polymers) developed at RRI can be inserted in the waveguide circuits for compensating the fanout loss and waveguide propagation loss [13]. Uniform optical fanout will be obtained by engineering the optical gain in the waveguide section between every two fanout gratings so that both the waveguide propagation loss and optical fanout loss can be exactly compensated. Note that the delay at each detector is equal to the time of flight along the waveguide circuit to the selected waveguide grating coupler. Because the length of waveguides is defined by photolithography, the proposed TTD module can provide a 0.1 ps true-time-delay resolution over a 50 ns dynamic range.

The non-blocking nature of the waveguide grating coupler allows us generate a large number of optical true time-delays (10^3 to 10^5) along the waveguide circuit where each fanout corresponds to a different true-time-delay. More importantly, its unique wavelength selectivity provides us an opportunity to employ wavelength-division-multiplexing technique. As a result, the optical true-time-delays for multiple communication links can be simply achieved by employing multiple RF modulated beams at different wavelengths over the same waveguide circuit. The optical RF signal received by detector is wavelength-selected by each grating coupler fabricated with a desired grating period. The demonstrated optical waveguide delay line is "optically transparent" in that it permits the simultaneous bi-directional travel of transmitted and received signals. The required optical RF carries in the range from few hundreds kHz to 100 GHz can be simply provided by using semiconductor-laser-based optical heterodyne technique [10,12].

Finally, the monolithic integration of detectors to the optical waveguides eliminates the most difficult optoelectronic packaging problem associated with the delicate fiber-detector interface and/or fiber-switch interface. Such a monolithic integration not only reduces the cost associated with optoelectronic packaging, but also reduces the system payload with an improved reliability. A significant reduction of cost, weight, and power consumption is expected.

The conducted approach will lead the development of a wideband compact multi-link optical true-time-delay line based on ultra-low-loss (0.02 dB/cm) polymeric waveguides. It will have all the advantages provided by conventional approaches while further reducing the system size and eliminating the complicated optoelectronic packaging problems associated with optical fiber-based delay lines. The benefits of the approach includes:

(1) Multiple communication links over wide RF spectrum up to 100 GHz,
(2) Large number of true-time-delays (100 to 10,0000) over a wide dynamic range (50 nanosecond) at 0.1 ps resolution,
(3) Compact and miniaturized structure in an integrated device scheme,
(4) Significantly reduced cost and weight,
(5) Simplified optoelectronic packaging,
(6) Potential integration with 100 GHz wideband polymer-based electro-optic modulators.

Realization of ultra-low-loss (0.02 dB/cm) polymeric waveguides represents a new technology that may create a new class of photonic devices with superior performance at a reduced cost.

2.0 PHASE I ACHIEVEMENT

During the Phase I research period, we have demonstrated the concept and feasibility of developing the optical true-time-delay technology for future broadband Phased Array Antennas applications. The theoretical feasibility is illustrated through our analysis of achieving microwave phasing at the antenna element level in the optical domain, thus demonstrated the high speed and high bandwidth potential of the proposed optical TTD lines. The optical waveguide circuit design of the optical TTD also demonstrated the concept of providing automatic phase control in a multiplexed configuration with characteristics of low cost, small payload, and easiness in photonic packaging. The practical verification of the proposed concept represents the main achievement of the Phase I research and the realized objectives are outlined as following:

1) An ultra-long polymeric channel waveguide has been successfully fabricated, which serves as the building foundation for the optical TTD circuits. The technical achievements include an ultra-long waveguide length of 10 meters, an ultra-low waveguide loss of 0.02 db/cm, and a determination of the optimal waveguide fabrication method (VLSI to be the most effective among the three techniques evaluated).

2) Surface normal polymeric waveguide gratings have been fabricated along the ultra-long channel waveguide, which provided optical fan out and controllable time-delay with photolithography precision. The achievements include large dynamic range of 50ns, high resolution of 0.1ps, and uniform optical fan out through waveguide amplification.

3) High speed and large bandwidth (60GHz) photodetector array has been fabricated onto polymeric waveguide circuit. A monolithic integration of waveguide circuits and the detectors demonstrated the simplicity of photonic packaging for the proposed optical TTD module.

4) Wavelength Division Multiplexing (WDM) technique has been successfully incorporated to realize multi-link broadband operation. The achievement lie in our concept demonstration of multi-link capability with a 4-wavelength generated twin-beam operation.

5) RF signal in the range of 11-50 GHz has been successfully generated with optical heterodyne detection of two wavelength-closely-situated optical signals at around 1550nm. The frequency determination of the 50 GHz microwave signal is obtained with a low bandwidth (25 GHz) detector through an innovative measurement method by frequency down-conversion.

The above practical demonstrations presented the feasibility of a future light-weight, low cost, and easy to fabricate photonic Phased Array Antenna based on the polymeric optical true-time-delay line proposed in this program. A complete technical description and achievements for the Phase I research period are further detailed in the following Section.

3.0 TECHNICAL DISCUSSION

3.1 Phased Array Antenna

The increasing demand on bandwidth for wireless communications either in military or civilian applications has recently stimulated technological advances in phased array antenna (PAA) research. To transfer information from ground stations to satellites (up-link), from satellites to satellites (inter-link), and from satellites to ground stations (down-link), the phased array antenna is currently the technology of choice which transmit and receive modulated RF frequencies at the greatest bandwidth possible among conventional broadcasting techniques. Present day phased array radar systems comprise a transmitter, receiver, beamformer, signal processor, display, power supplies, and a large number of transmit/receive modules that are at some distance from the central location and in close association with the antenna elements making up the array. For airborne applications, the active electronic device of such radar systems are solid state devices configured as discrete devices on printed circuit boards, integrated circuits on silicon substrate, hybrid integrated circuits, and monolithic microwave integrated circuits, which are small, light weight, and miniaturized. The realization of practical, photonic phased antenna arrays is currently hampered by the extreme complexity required in efficiently transmitting several hundred signals and microwave delays from the input control to the antenna array of the system. These difficulties are compounded by the demands of advanced phased array systems, where optical true-time-delay techniques have to be employed for wideband applications.

The phased array antenna technology has been the principal method for airborne and space-borne data and voice transmission and receiving based on Radio Frequency (RF) or microwave analog modulation. The electronic phasing of individual antenna elements has revolutionized the PAA technology by offering electronically directive beam steering. In phased array antenna, the transmitted radiation pattern is a superposition of the elemental patterns from each individual antenna element. Such a superposition contains the applied element weights (voltages or currents) of the incident signal, which modulates the vector summation of the elemental patterns. The applied element weights, depending on its form, provide a phase control to the vector summation and thus determine the pattern outcome of the PAA. The beam propagation direction is fully determined by the element weights and can be electronically controlled. Most commonly, phase shifters are used to provide the element phase factors to scan the antenna pattern. In this approach, the peak of the array pattern is located at certain frequency of the radiating signal. Such frequency dependence limits the bandwidth of the PAA, indicating a desired steering direction only for a certain frequency. Another way of elemental phase control can be realized by switching the actual time delays of electronic feeds to each antenna element. In this case, the element weights can be chosen as complex conjugates of the element positional vector, which render the superposition of the elemental patterns to be frequency independent. Practically, this corresponds to inserting time delays or lengths of transmission line that have a path length difference for the array locations compensated, so that the signals from all elements arrive together at some desired distant point, independent of signal frequencies. A true-time-delay phase control approach is the foundation for broadband Phased Array Antennas.

Figure 3 illustrates the radiation patterns of a 24 elements (3x8) phased array antennas at three different RF frequencies. The overall similarity of the zero-degree scan pattern distribution among the three different frequencies indicates frequency independent operation when true-time-delay phase control is incorporated. The simulation show 9° beamwidth for a 3x8 elements phased array antennas. Narrow beamwidth can be obtained by employing a large number of antenna elements. For a practical application, a minimum of 16x16 elements is required in a phased array antenna.

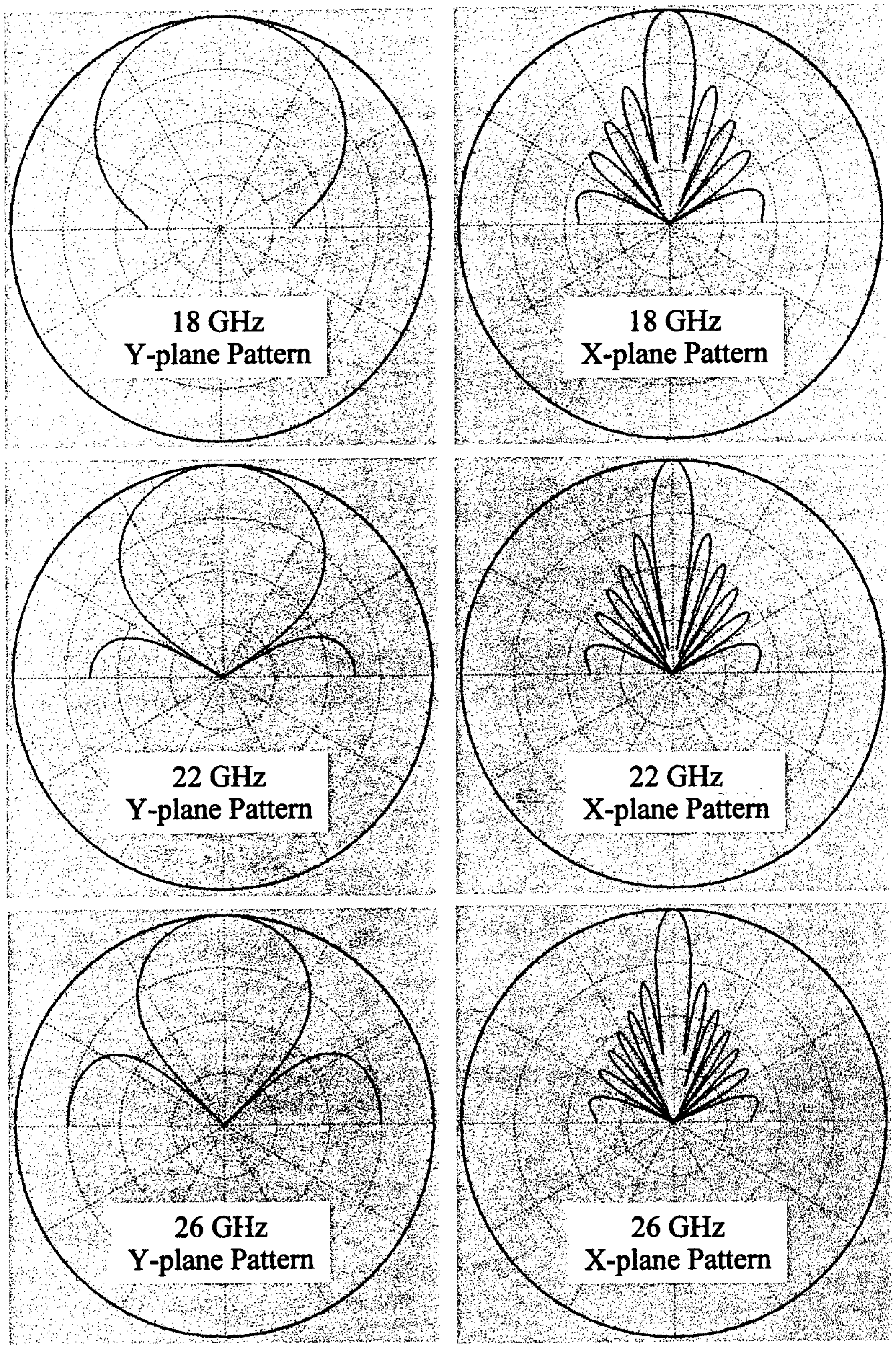


Figure 3. Simulated radiation patterns for zero-degree antenna scan.

3.1.1 The State-of-The-Art in Photonic Phases Array Antenna

As discussed in the above section, traditionally, beam-forming and steering of phased array antennas are performed by individually controlled phase shifters and variable gain amplifiers in the signal path of each array element. For large arrays, the hardware necessary to perform this beam forming function becomes prohibitively complex and heavy. The high prime-power consumption of active phase shifters is a sever disadvantage in many applications. Therefore light-weight and low power consumption PAA systems have been developed to take the advantage of compactness offered by photonics technology.

The current state-of-the-art includes (1) Fourier-Optic Beamforming: a method employing coherent optics, i.e., a Fourier transform (FT) lens, to form a scaled spatial FT of the desired antenna beam shape and direction, and sampling this optical transform via heterodyne detection to generate a RF signal set that drives the antenna array. Then, the far field free space propagation operation implements the FT of the RF antenna radiated energy, forming the desired RF beam in space [14]. (2) Fiber-Optic RF Phase Control: a method employing optical fiber as delay lines configured to act as a beamformer, which has the advantage of high phase accuracy and high resistance to EMI [15]. (3) Integrated-Optic RF Phase Control: optical control on the phase and amplitude of microwave was realized through integrated electro-optic devices such as lithium niobate power-splitter waveguide phase shifters and acousto-optic Bragg cell for frequency shifting. Multichannel signals with individually controlled phase information are generated by mixing the optically phase-shifted reference beams and frequency-shifted Bragg cell signal in fiber-optic receivers [16]. (4) Acousto-Optic Liquid-Crystal Phase Based Beamforming: Nematic liquid crystals (NLC) and acoustooptic devices were used for phase-based phased array control. The desired analog phase control is achieved by the analog nature of the electrically controlled motion of the birefringent NLC molecules. As the electrical field is applied to NLC, its molecular rotation induces a refractive index change experienced by the incident light beam that is polarized along the NLC molecular axis. This change in index causes the light beam to suffer an optical phase shift, which is converted to a RF phase shift after interferometric detection at an output photodetector [17]. (5) RF Phase Control via Optical Injection Locking of Microwave Oscillators: the method achieves RF phase control by injection of an optical signal into a microwave oscillator, analogous to electrical injection locking of the microwave oscillator by an electrical signal. An accurate $\pm 90^{\circ}$ RF analog phase control can be achieved [18]. (6) Integrated Optical Switching Based Time Delays: cascaded optical 2x2, 4x4, or 8x8 switch matrix can be employed with optical fiber delay lines to achieve bi-directional (transmission and receiving) time-delay operation, which serve as high-performance optoelectronic "building block" elements [19].

In summary, the major accomplishments of the herein listed photonic techniques for PAA phase control lie in their great reduction of payload, decreased power consumption, and increased bandwidth. True-Time-Delay (TTD) technique for antenna phase control, in particular, has removed the frequency dependence or "beam squint" of PAAs, thus increasing the bandwidth of the PAA systems.

3.1.2 Optical True-Time-Delay for Phased Array Antennas

The phased-array antennas traditionally employ electronically driven antenna elements with individually controllable phase-shift. The wavefront direction of the total radiated carrier wave is thus controlled through continuously and progressively varied phase shift at each radiating element, achieving a continuous steering of the antenna. For a linear array radiating elements with individual phase control, the far field pattern along the direction of Φ can be expressed as [1]

$$E(\Phi,t)=\sum_{n=0}^{N} A_n \exp(i\omega_m t)\exp[i(\psi_n + nk_m \Lambda \sin\Phi)] \ , \quad (1)$$

where A_n is pattern of the individual element, ω_m is the microwave frequency, $k_m = \omega_m / c$ is the wave vector, ψ_n is the phase shift, Λ is the distance between radiating elements and Φ is the direction angle of array beam relative to array normal. The dependence of the array factor on the relative phase shows that the orientation of the maximum radiation can be controlled by the phase excitation between the array elements. Therefore, by varying the progressive phase excitation, the beam can be oriented in any direction. For continuously scanning, phase shifters are used to continuously vary the progressive phase. For example, to point the beam at an angle Φ_0, ψ_n is set to the following value,

$$\psi_n = -nk_m \Lambda \sin\Phi_0 . \quad (2)$$

Differentiating Equation (2), we have

$$\Delta\Phi = -\tan\Phi_0\left(\frac{\Delta\omega_m}{\omega_m}\right) \quad \text{(rad)}, \quad (3)$$

It is clear that for a fixed set of ψ_n's, if the microwave frequency is changed by an amount $\Delta\omega_m$, the radiated beam will drift by an amount $\Delta\Phi_0$. This effect increases dramatically as Φ_0 increases. This phenomenon is the so-called "beam squint", which leads to an undesirable drop of the antenna gain in the Φ_0 direction.

In order to obtain the ultrawide bandwidth, it is necessary to implement true-time-delay steering technique such that the far field pattern is independent of the microwave frequency [3]. In the approach of true-time-delay, the path difference between two radiators is compensated by lengthening the microwave feed to the radiating element with a shorter path to the microwave phase-front. Specifically, the microwave exciting the (n+1)th antenna element is made to propagate through an additional delay line of length $D_n = nL(\Phi_0)$. The length of this delay line is designed to provide a time delay

$$t_n(\Phi_0) = (n\Lambda \sin\Phi_0) / c \quad (4)$$

for the (n+1)th delay element. For all frequencies ω_m, ψ_n is given by

$$\psi_n = -\omega_m t_n(\Phi_0) . \quad (5)$$

3.2 Optical True-Time-Delay Lines Based on Polymeric Waveguide Circuits

For high-speed and broadband operation of phased array antennas, the true-time-delay microwave phase control can be realized in optical domain. Such optical delay lines have traditionally been built with optical fiber, which suffer from difficulty in providing large number of optical fanouts and accurate delay lengths.

Optical polymer has recently shown great potential in fabricating practical photonic waveguide devices. Because polymeric waveguide technology is concept ional hybrid, it opens up the possibility for large scale optoelectronic integration on any substrate in a cost effective manner. In this Phase I program, we have taken a new approach for developing wideband phased array antennas using polymeric waveguide technologies [21]. In this approach, optical true-time-delay lines are made out of photonic polymeric waveguide circuits integrated with electrically switched high-speed photodetectors as shown in Fig. 2. This PAA system uses an ultra long polymeric channel waveguide circuit on a semiconductor substrate, where a high-speed photodetector array is pre-fabricated. The optical true-time-delay circuits consist of (1) polymeric channel waveguides, (2) waveguide grating couplers, and (3) fast switched photodetectors. Such a polymeric waveguide circuit is capable of providing optical true-time-delays from 1 ps to 50 ns for wideband multiple communication links in a compact miniaturized scheme. Note that the bandwidth of this approach is currently limited by the bandwidth of photodetectors at 60 GHz. Optical heterodyne technique is used for generating an optical RF carrier by employing two coherent laser diodes with slightly different wavelength. A large number of true-time-delay combinations can be provided for the phased-array antenna simultaneously by electronic switching on-and-off photodetectors fabricated under the polymeric waveguide circuits. This system eliminates the need for fast wavelength tunable laser diodes, long bulky bundles of fibers and/or expensive optical 2x2 waveguide switches. Unlike any conventional approach where one TTD line can provide only one delay signal at a time, this true-time-delay module is capable of generating all required optical true-time-delay signals simultaneously to all antenna elements.

Compared to expensive electro-optic switches and wavelength tunable laser diodes, high performance photodetectors are inexpensive and can be cost-effectively fabricated into a large array based on the technologies originally developed for optical imaging and fiber-optic communications. High-speed Newport MSM photodetectors have a bandwidth up to 60 GHz or a rise time of 7 ps. The optical and electric diagram of the detector-switched optical true-time-delay module is further described in detail in Section 3.2.1. Such a hybrid integration of detectors to the optical waveguides eliminates the most difficult optoelectronic-packaging problem associated with the delicate fiber-detector interface and/or fiber-switch interface. It not only reduces the cost associated with optoelectronic packaging, but also reduces the system payload with an improved reliability for airborne applications. The delay at each detector is equal to the time of flight along the waveguide circuit to the selected waveguide grating coupler. Because the length of waveguides is defined by photolithography, the optical polymeric waveguide delay lines can provide an 0.1 ps resolution over a 50 ns dynamic range. The thin film nature of polymers allows us to fabricate the TTD module (made out of waveguide circuits and waveguide gratings) on any substrate of interest, using standard VLSI technologies originally developed for microelectronics industries.

3.2.1 Novel Concept of Detector-Switched Optical True-Time-Delay Lines

The conceptual approach of the compact detector-switched multi-beam optical true-time-delay module is shown in Fig. 4. It consists of a long ultra-low-loss polymer-based channel waveguide in conjunction with an array of surface-normal waveguide grating couples that fanout the RF modulated optical beams to each corresponding photodetector, respectively. The photodetector array and polymeric channel waveguide circuit are fabricated in the same substrate. The true-time-delayed RF modulated optical signal is converted to RF electrical signal by the photodetector. A specific delay is selected by switching on the bias of the photodetector, which is accomplished in the electrical domain via a voltage-controlling transistor in the bias circuit. The true-time-delays for multiple communication links can be simply provided by employing multiple RF modulated beams at different wavelengths (λ_1 and λ_2) over the same delay line based on wavelength-division-multiplexing technique.

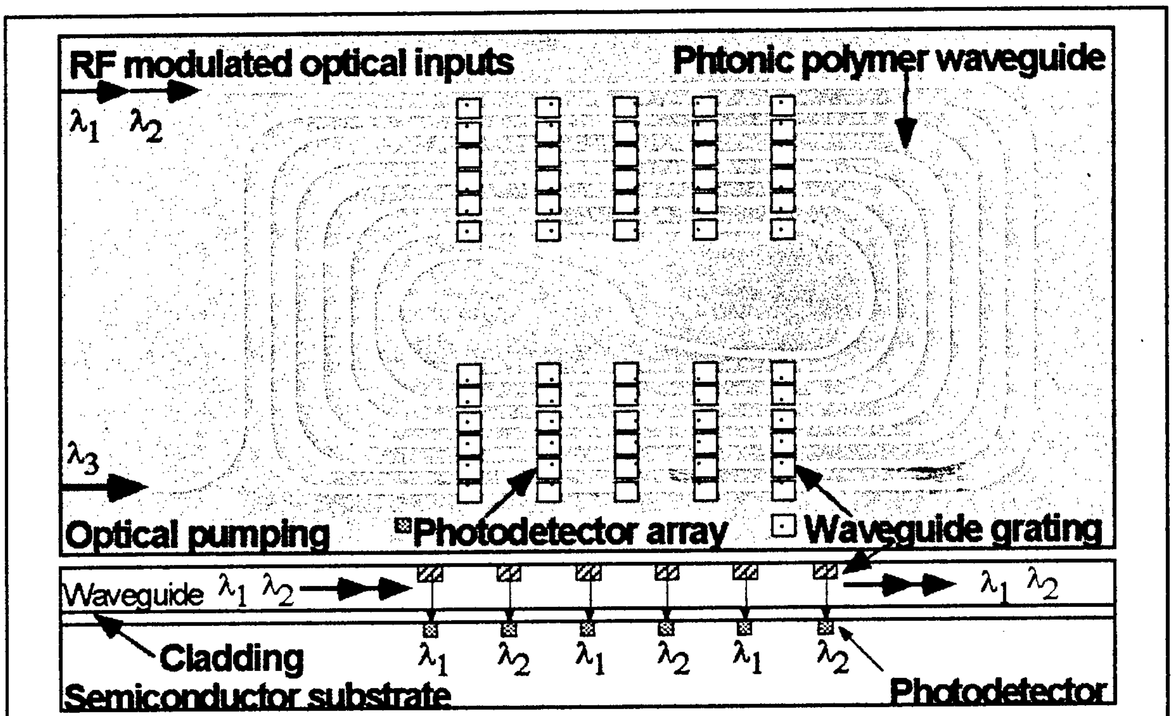


Fig. 4. Schematic diagram of the proposed compact multi-link optical true-time-delay line based on an ultra-low-loss waveguide. (a) Top view and (b) side view.

The delay at each detector is equal to the time of flight along the waveguide circuit to the corresponding waveguide grating coupler (see Fig. 4). The ultra-low-loss polymeric waveguide in conjunction with polymeric waveguide amplifier allows us to fabricate a large number of fanout gratings over a very long optical channel waveguide. The thin film nature of polymers allows us to fabricate the proposed device (waveguide circuits and waveguide gratings) on any substrate of interest, using standard VLSI technologies originally developed for microelectronics industries. The detector switched optical TTD line is further illustrated with electronic switching diagram in Figure 5.

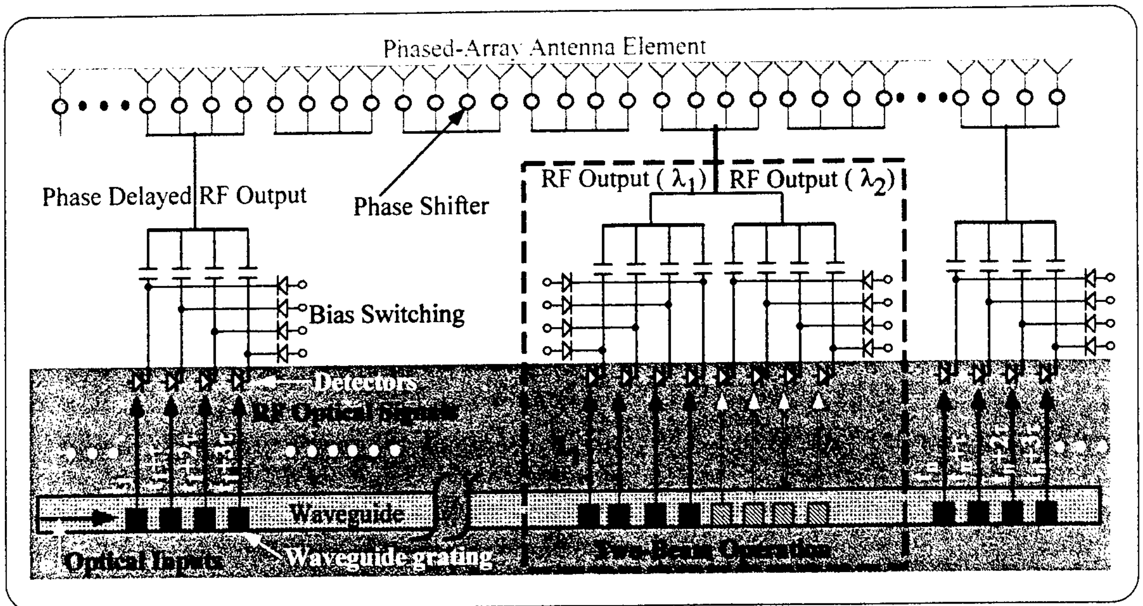


Fig. 5. Schematic diagram of the proposed detector-switched optical waveguide true-time-delay line for photonic phased-array antennas.

There are four crucial building blocks that need to be demonstrated to show the feasibility of the proposed compact waveguide true-time-delay lines. They are (1) ultra-low-loss polymeric waveguide and polymer-based waveguide amplifier, (2) wavelength selective grating fanout couplers for employing WDM technique, (3) very long optical channel waveguide circuits, and (4) generation of wideband RF signal using semiconductor-laser-diode based optical heterodyne technique. It should be noted that the switched photodetector array are commercial available for fiber-optic telecommunication industries. The technical details for constructing these four building blocks are given in the following.

3.2.2 Optical Fanouts Based on Waveguide Grating Couplers

The waveguide grating coupler is an ideal candidate to fanout the guided-wave optical RF signals to photodetectors as shown in Fig. 2 and Fig. 4. The unique non-blocking feature allows us to have a large number of optical fanouts from multiple laser beams along the waveguide propagation. The strong wavelength-selectivity of grating couplers provides us an opportunity to employ multiple beams in the same delay line for multi-link PAA system, based on wavelength-division-multiplexing technique.

The optical waveguide grating coupling is an ideal candidate for coupling out the RF modulated optical waves into photodetectors, which propagate through the polymeric waveguide circuit. The unique non-blocking feature of gratings allows us to have a large number of optical fanouts along the waveguide propagation, where each fanout corresponds to a true-time-delay. Since the polymer-based waveguide delay lines are fabricated in a planarized geometry, while the photodetector array employed receives optical signal perpendicular to the substrate surface, surface-normal optical grating couplers are required. In order to provide effective surface-normal coupling, the microstructure of grating coupler should be tilted for creating the required

Bragg phase-matching condition just for one output direction. Such surface-normal waveguide grating couplers can be achieved by using tilted surface relief microstructure [9,10] and/or volume holographic dispersive gratings [11,12].

In Phase I, we have successfully developed a reliable new technology for fabricating tilted gratings that provide surface-normal fanout at a desired wavelength. The optimum tilted angle is investigated together with VLSI fabrication processes. This has allowed us to fabricate the proposed waveguide delay lines using standard fabrication technologies originally developed by microelectronics industry, which is the key to achieve low-cost, high-quality, mass-producible devices required by the advanced PAA systems. We have chosen the standard VLSI fabrication technologies to produce surface-relief tilted waveguide gratings in our research. Conventional grating coupler has an inherent drawback of power loss due to bi-directional diffraction. The most effective technique for overcoming this problem is to employ tilted gratings. In order to obtain an optimum coupling, we first determine the optimum grating period and tilted angle.

In the coupling geometry shown in Fig. 6, we can determine the required grating period Λ as a function of diffraction angle θ_m, diffraction order m, operating wavelength λ, refractive index of waveguide n_1 and refractive index of cladding n_2. The required grating period based on phase-matching condition is

$$\Lambda = \frac{m\lambda n_1}{n_2 \tan\theta_m}[1+\tan^2\theta_m]^{1/2} \quad (6)$$

If we assume n_1 and n_2 are the refractive index of the superstrate and grating tooth, respectively, the geometrical average of the squared refractive index in the grating region is given by

$$n_g^2 = n_1^2 d + n_2^2(1-d), \quad (7)$$

where d is the toothwidth-to-period ratio. The optimum tilted angle for first-order Bragg diffraction is given by

$$\theta_{Tilted} = \arccos\frac{\lambda_o}{\Lambda\sqrt{n_g^2 - n_{eff}^2 + \frac{2n_{eff}\lambda_o}{\Lambda}}} \quad (8)$$

where n_{eff} is the effective index of the waveguide structure including the grating, and Λ is the grating period given by Eq. (8).

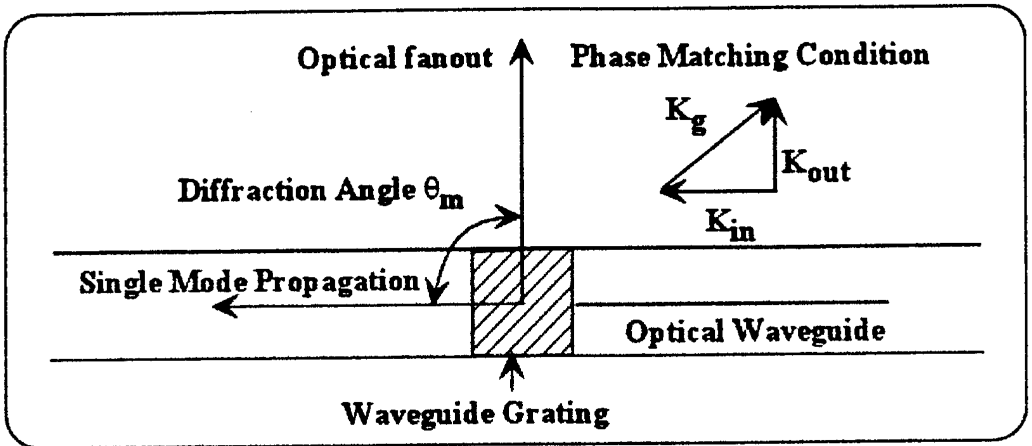


Fig. 6. Schematic of a waveguide grating coupler and its phase-matching diagram.

3.2.3 Multi-link Operation by WDM Technologies

To provide the multi-link optical true-time-delay (TTD) functionality, wavelength-division-multiplexing technique can be employed in conjunction with polymeric waveguide grating couplers. Waveguide grating couplers are ideal for producing a large number of optical RF modulated TTD signals to photodetectors when WDM technique is employed for multi-link communications. The unique non-blocking feature allows us to have a large number of optical fanouts from multiple laser beams along the waveguide propagation. Because of the strong wavelength selectivity of optical gratings, waveguide gratings can be designed and fabricated to diffract light at a desired wavelength by adjusting grating period. In other wards, it can function as a wavelength-division-demultiplexer in the waveguide delay line circuits when multiple laser beams are used for multiple communication links.

To demonstrate the concept of a simple multi-link approach, a set of waveguide surface-normal grating couplers with operating wavelengths of λ_3 = 1550 nm are fabricated over a polymeric waveguide delay line. In the experiment, three laser beams with output wavelength at λ_1 = 950 nm, λ_2 = 1300 nm, and λ_3 = 1550 nm, respectively, are employed and coupled into the testing waveguide delay line as shown in Fig. 7.

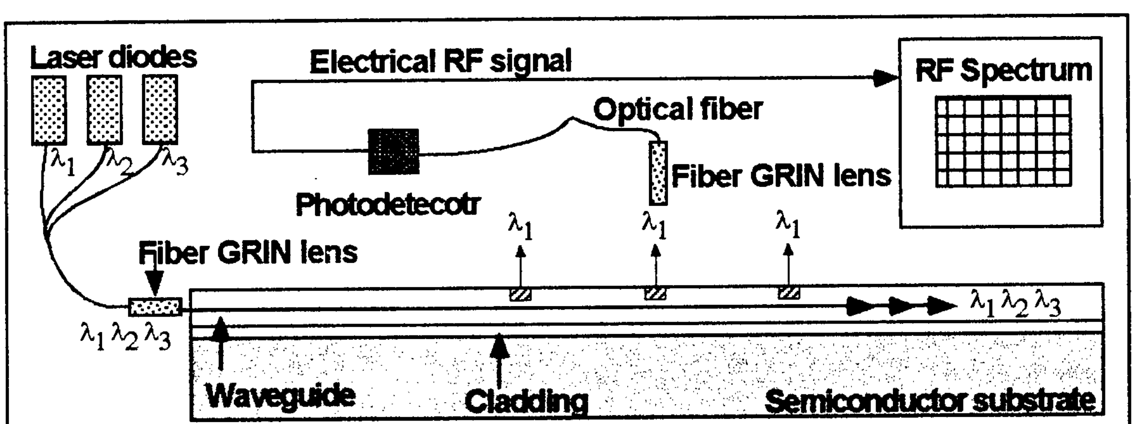


Fig. 7. Schematic of a multi-link waveguide delay line using WDM technique.

To determine the optical crosstalk among the multiple channels, three input lasers are further amplitude-modulated at three different frequencies (0.9 MHz, 0.7 MHz and 1.1 MHz) respectively. This allows us to separate the measured crosstalk and signal on the display screen, simultaneously. The input power of each modulated laser beam was adjusted at the same level (~500 μW). The optical output from a grating coupler was detected by a fiber pig-tailed photodetector through a fiber GRIN lens. In the experiment, the detector was positioned at the waveguide grating coupler designed for surface-normal coupling at λ = 1550 nm. The fabricated waveguide grating has a 30 μm interaction length with a coupling efficiency of 5%. The optical crosstalk was measured by a RF Spectrum Analyzer (Model hp 8566B). The channel crosstalk was successfully determined at a signal-to-noise ratio (SNR) of 32 dB as shown in Fig. 8. A tunable laser with a wavelength tuning range from 1470 nm to 1650 nm was further used to determine the coupling window of waveguide gratings. The measured transmission spectrum had a 40 nm 3-dB linewidth with 100 nm wavelength separation between the first two minima.

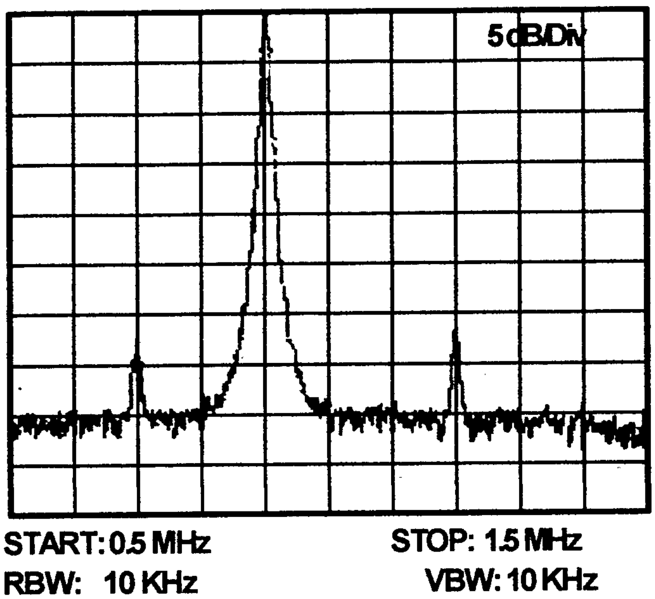


Fig. 8. Measured optical signal at λ_1 =1550 nm and cross talks from other two channels at λ_1 = 950 nm and λ_1 =1300 nm, respectively.

3.2.4 Optical RF Generation Using Heterodyne Technique

To provide the ultra wideband operation from 11 GHz to 40 GHz, required by broadband PAAs, several RF techniques can be employed with different bandwidth tunable capabilities. These include harmonic generation in a Mach-Zehnder modulator [22], heterodyne mixing of two lasers [23], resonance enhanced modulation of a laser diode (LD) [24], and a dual mode DFB laser in mode-locked operation [25]. Direct modulation of laser diode seems straightforward to generate millimeter wave. However, the high insertion loss, high drive voltage, nonlinear response and small modulation depth limit the usefulness of this technique [26].

Compared with direct modulation of a laser diode (LD) or using external modulators, optical heterodyne technique is capable of providing hundreds of GHz base bandwidths while maintaining high modulation depth. In Phase I, we have successfully generated up to 50 GHz RF signals by using two tunable diode lasers oscillating at single longitudinal mode based on optical heterodyne technique. Fig. 9 shows the schematic diagram of the experimental setup. The outputs from these two lasers with slightly different wavelengths are combined by a 2-to-1 polarization maintaining fiber beam combiner and then sent to wideband photodetector.

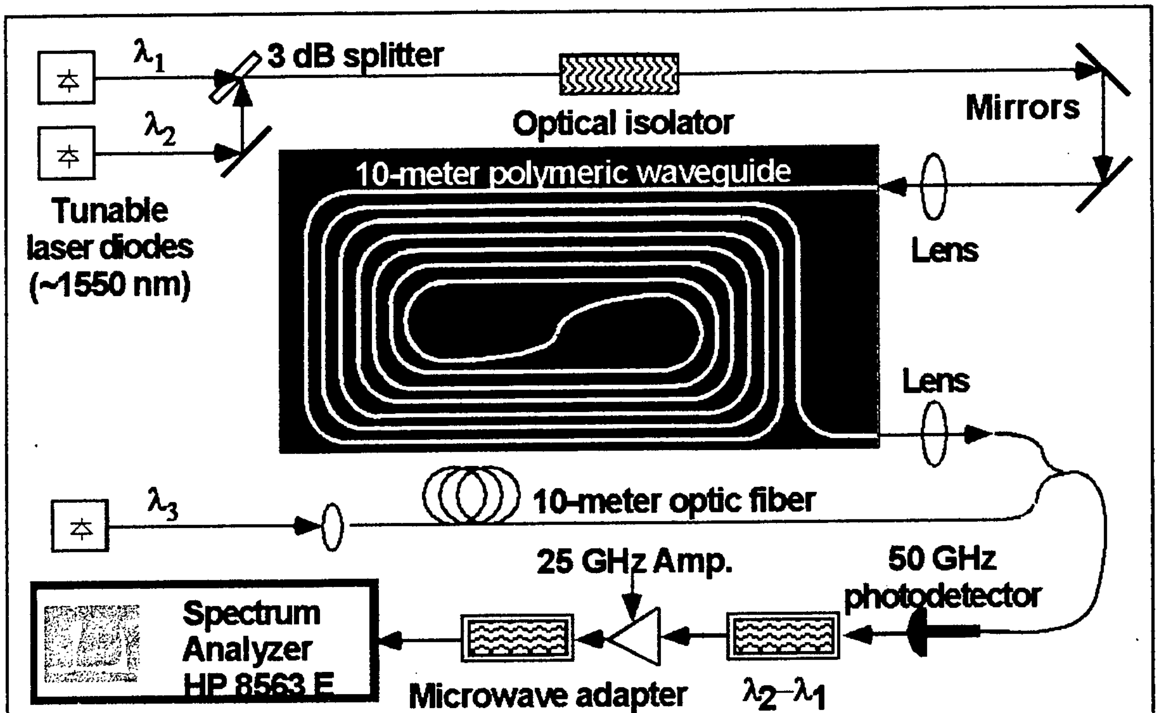


Fig. 9. Generation of RF signals by using optical heterodyne technique.

Suppose that the outputs of these two lasers are given by

$$E_1(t) = A_1 \exp(j\omega_1 t), \quad \text{and} \tag{9}$$

$$E_2(t) = A_2 \exp(j\omega_2 t) = A_2 \exp[j(\omega_1 + \Delta\omega)t], \tag{10}$$

where $\Delta\omega$ is the beat frequency. The output of the photodetector is given by [22]

$$i_d(t) = \frac{e\eta}{hv}[A_1^2 + A_2^2 + 2F(\Delta\omega)A_1A_2\cos(\Delta\omega)t], \tag{11}$$

where e is the electron charge, η is the quantum efficiency of the detector, $h\upsilon$ is the photon energy, and $F(\Delta\omega)$ is the frequency response function of photodetector.

Due to the limitation of the bandwidths of the detector, amplifier, and the spectrum analyzer, this 50GHz signal cannot be detected directly. To solve this problem, a third tunable diode laser with wavelength between the above two lasers is used to down-convert this 50 GHz signal to two signals at about 25 GHz. This 50 GHz signal was sent directly through the optical waveguide delay line fabricated. The optical fanout from the waveguide TTD line is combined with the output of the third laser and is then sent to ultra-fast photodetector with a 25 GHz microwave amplifier, which is connected to a RF spectrum analyzer. From the measured signals shown in Fig. 10, we get

$$\Delta\omega=\omega 1-\omega 2=(\omega 1-\omega 3)+(\omega 3-\omega 2)=24.85+25.90=50.75 \text{ (GHz)}. \qquad (12)$$

Presently, the 50 GHz result is limited only by the frequency responses of the detector, the amplifier, and the spectrum analyzer, but not the optical waveguide true-time-delay module. Since a small tune of the laser wavelength (a few Å) will provide a large beat frequency (tens of GHz), microwave signals as high as several hundred GHz can be readily generated.

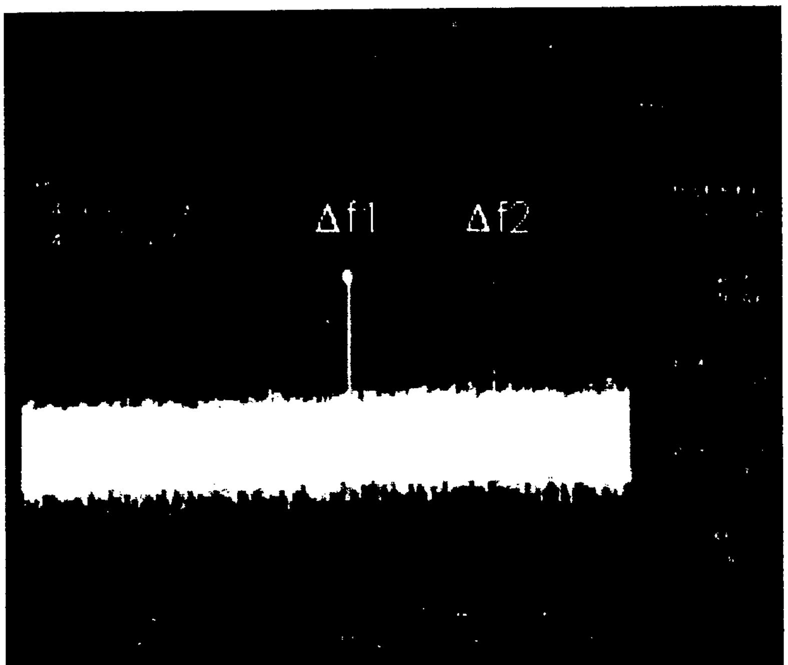


Fig. 10. 50 GHz signal indicated by two 25 GHz signals on the RF spectrum analyzer.

3.3 Polymer-Waveguide Fabrication Technology for Optical TTD at RRI

In order to implement the polymer based photonic circuit for optical true-time-delay, an ultra-long and ultra-low loss channel waveguide with large dynamic range must be fabricated. Such a waveguide will serve as the optical delay backbone for light beam propagation. Surface normal fan out gratings need to be fabricated on the waveguide backbone for precision delay control. Monolithic integrated photodetectors for heterodyne generation of microwave signal must be fabricated on top of the polymeric waveguide, vertically overlapping the surface normal fanout gratings. We have investigated three fabrication methods including compression molding, VLSI lithography, and laser writing techniques for polymer waveguide formation. For waveguide grating fabrication, we have chosen reactive ion etching (RIE) technique, which is a well-developed precision micro-fabrication process in silicon industry. Its highly effectiveness in producing straight side-walls is best suited for tilted waveguide grating formation. For photodetector fabrication, we have employed Si/SiO2 resonant-cavity and have also fabricated high speed InGaAs photodetector/InP p-HEMT amplifier in collaboration with our industrial partner.

3.3.1 Fabrication of ultralong and ultralow loss polymer waveguide

To realize a high performance phased array antenna, the optical polymeric waveguide may need to be over 10 meters for providing sufficient optical true-time-delay. To fabricate such ultra-long polymeric waveguide circuits, we have developed three waveguide fabrication technologies [19,28-30]:

- Compression-molding technique,
- VLSI lithography technique, and
- Laser-writing technique.

Fig. 11 shows the schematic diagrams of three waveguide fabrication technologies. Our experimental results indicate that high performance polymeric waveguide circuits with waveguide propagation loss less than 0.02 dB/cm can be produced by using laser-writing technique. Compression-molding technique has demonstrated its uniqueness in producing three-dimensional (3D) tapered waveguide circuits, which is crucial for obtaining efficient optical coupling between the input laser diode and the waveguide circuit. Mass-producible waveguides with excellent repetabitivity have been obtained by using VLSI lithography technique, originally developed for fabricating very large scale integrated circuits on silicon wafer.

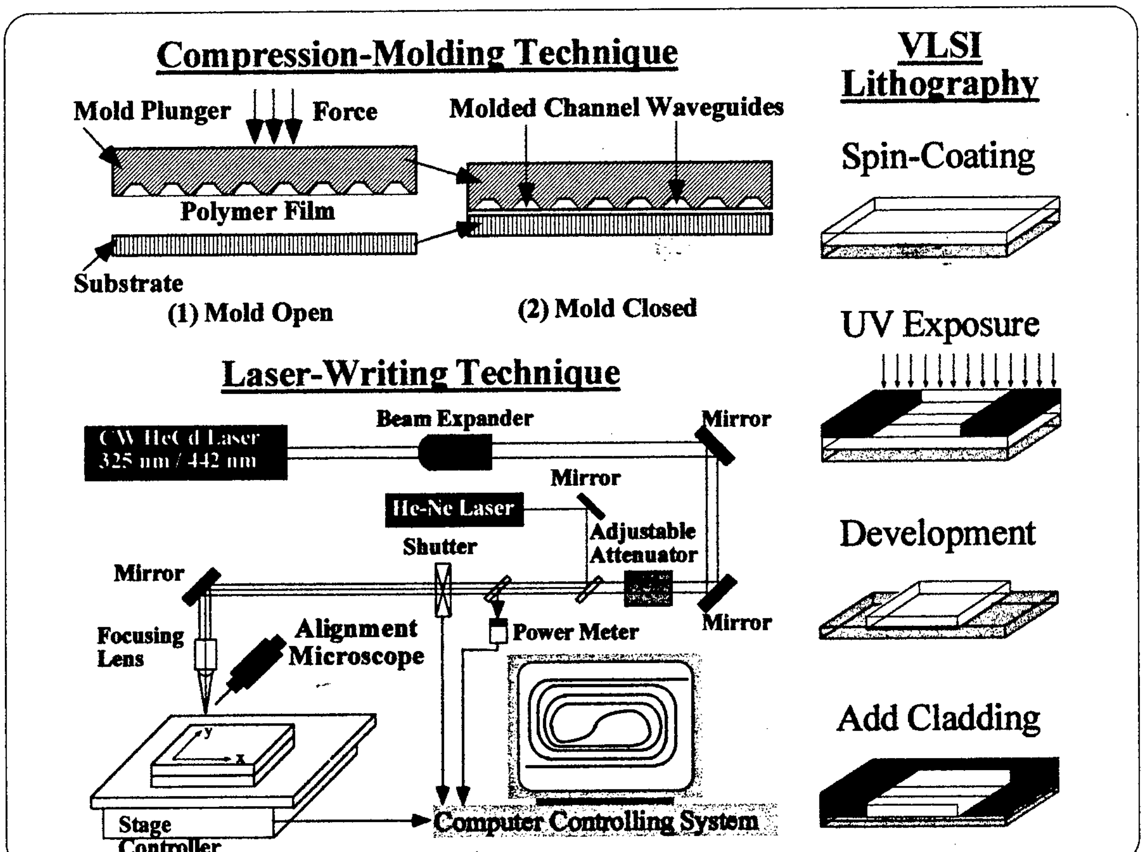


Fig. 11. Schematic diagrams of three polymeric waveguide fabrication technologies developed at Radiant Research, Inc..

(1) Compression-molding technique

We have firstly investigated the compression-molding technique for fabricating polymer-based channel waveguides[30]. The process of compression molding is described by reference to Fig. 3.22. A two-piece mold provides a cavity having the shape of the desired polymer-based channel waveguide array. The mold is heated to a desired temperature that is often above the glass transition temperature. An appropriate amount of molding material, polymer waveguide film in this case, is loaded into the substrate. The molding process is conducted by bringing two parts of the mold together under pressure. The polymer film, softened by heat, is thereby welded into the shape of the stamp. The molding process is performed during the phase transition period within which the polymer film is deformable. The compression-molded polymeric waveguide presented herein is probably the only solution to bridge a huge dynamic range of different optoelectronic device depths varying from few microns to few hundreds microns. High performance polymeric waveguides can be obtained at low cost with this compression-molding technique.

A 45-cm long polymer-based compression-molded channel waveguide was fabricated on a glass substrate as shown in Fig. 12, where a microprism was employed to couple a HeNe laser beam (0.6328 mm) into the waveguide. The phase matching angle was set for the fundamental waveguide mode. Waveguide propagation losses of different samples were measured by using the two-prism method [5]. Waveguide loss of 0.5 dB/cm was experimentally confirmed at 632.8 nm. Waveguide loss at 1300 nm was measured from 0.2 to 0.5 dB/cm. In Fig. 12, the channel waveguide fabricated had a rib width (W) of 110 μm, a groove depth (T_2) of 8 μm and a cladding layer thickness (T_1) of 2 μm.

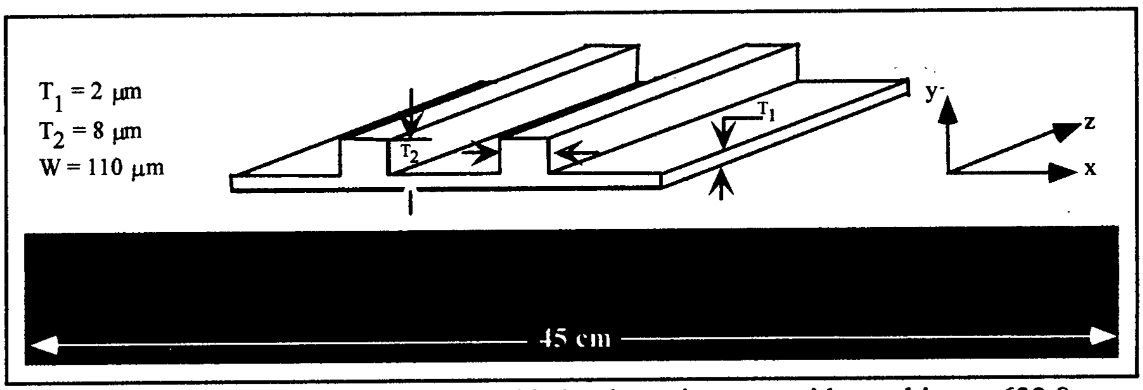


Fig. 12. A 45 cm long compression-molded polymeric waveguide working at 632.8 nm.

Fig. 13 shows the 3D tapered waveguides fabricated by the compression-molding technique using the photonic polymer developed. The molding tool that we employed has a waveguide width and height of 5 μm at the small end. It is 3D linearly tapered with a waveguide width and height of 100 μm at the large end. A small section of the molded polymer waveguide is shown in Fig. 14 where the 3D tapering is clearly indicated. The waveguide thus fabricated demonstrated multiple modes without a cover cladding. However, it exhibits single-mode operation at the small end if a polymeric cladding layer is further spin-coated on it. The pressure between the molding plunger and glass substrate determines the waveguide thickness. The exclusive characteristic of the polymer thin film, i.e., photolime gel employed herein, has the graded index (GRIN) distribution which allows us to fabricate these molded waveguide devices on any substrate of interest regardless of the substrate refractive index and conductivity [28,30].

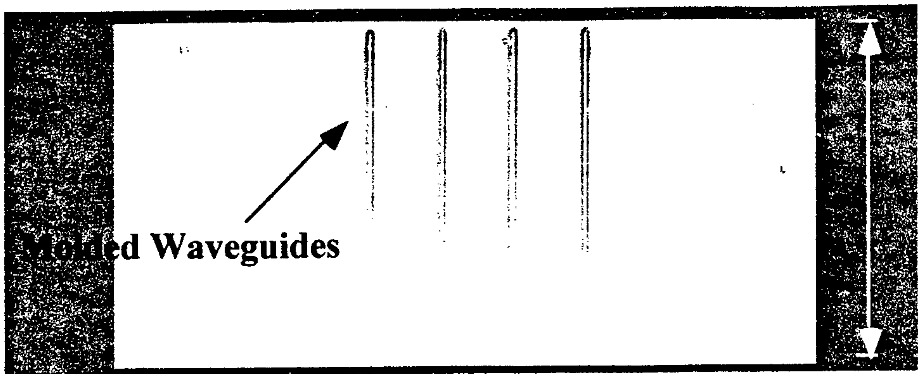


Fig. 13. Photograph of compression-molded 3D tapered polymeric waveguides.

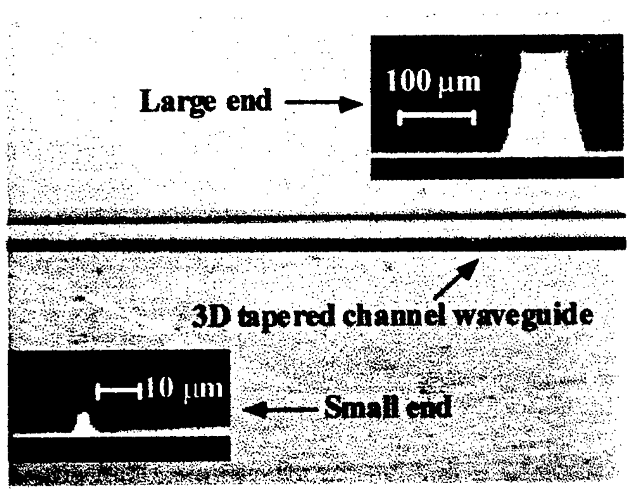


Fig. 14. Photo of a small section of the molded 3D linear tapered waveguides

(2) Laser-writing technique

The laser-beam waveguide writing system was also investigated for fabricating high performance polymer-based channel waveguides[9]. The laser-beam writing system employed is shown in Fig. 11, which consists of a dual-wavelength HeCd laser (λ_1 = 325 nm and λ_2 = 442 nm), beam-shaping optics, an electronic shutter and a computer-controlled X-Y-Z translation stage with a stroke of 30 x 30 x 2.5 cm^3. The stage translation speed is continuously adjustable below 1.0 cm/s. The positioning resolution is 0.5 μm and 0.01 μm for the X-Y axes and Z axis, respectively. The Z-stage is employed to precisely control the focused laser beam sizes. Fig. 15 shows a polymeric waveguide H-tree fabricated on a silicon wafer by using laser-beam writing technique. The waveguide propagation loss is measured at ~0.02 dB/cm, which is the lowest loss demonstrated ever in polymer-based channel waveguides. The waveguide width and depth were 100 microns and 10 microns, respectively.

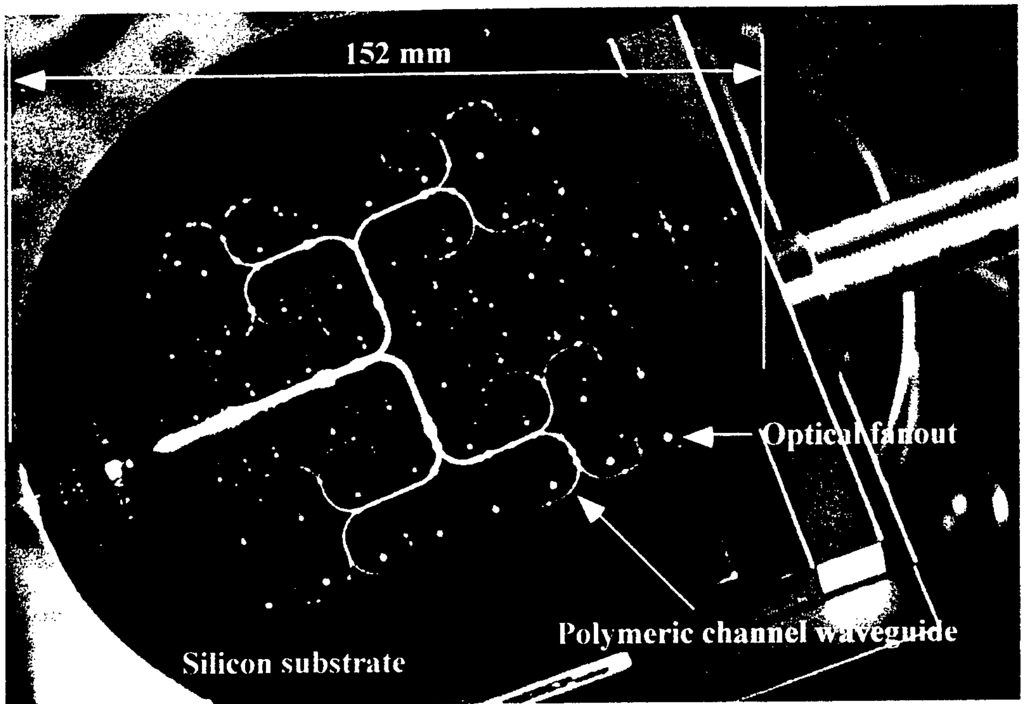


Fig. 15. Photograph of a polymeric waveguide H-tree fabricated on a silicon wafer.

Laser formed polymeric channel waveguides are based on a unique technique developed by Radiant Research, Inc., called internal polymer diffusion (IPD) as shown in Fig. 16. The processes exploit the polymeric property that high mobility low molecular weight monomers can rapid diffuse within a polymeric matrix. The process can be designed to be dry or wet, with no etching or molding required. The waveguide formation is completely laser-beam induced followed by photo and/or thermal fixing. Smooth, low scatter waveguide side walls are produced resulting in optical losses inherently identical to the bulk materials. This results from having waveguide edges within the guide layer defined by monomer diffusion, induced by laser-beam writing and photopolymerization processes, and from having the waveguide top and bottom defined by the coated film surfaces that are flat to tens of nanometers.

The laser-beam writing technique is a straightforward process with minimal equipment and steps, uses dry, pre-coated and pre-quality controlled materials, and is amenable to large area exposures, as opposed to etching, molding, or embossing procedures. In Fig. 18, the diffusion is the dominant mechanism for forming large uniform waveguides at low propagation loss. The waveguide and cladding layers are distinctly different formulations to create desired optical refractive indices. Typically, power is around 2 mW/cm^2 and the energy is 10 mJ/cm^2 using HeCd laser at a wavelength of 325 nm. Crosslink processing is conducted by UV exposure or thermal baking, which is set usually at 135°C for 2 hours.

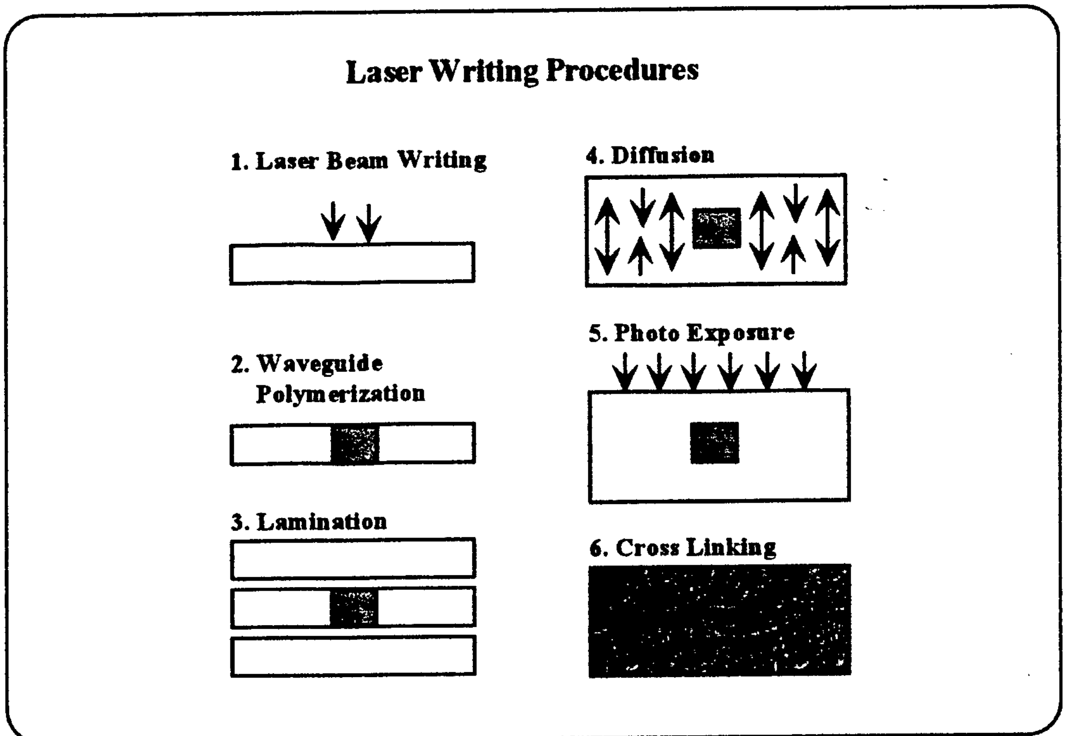


Fig. 16. Schematic of the process steps for laser beam writing technique.

The ability to progressively laminate and bond successive layers to build up polymeric waveguide structures provides a significant and essential attribute for performance, applicability and manufacturability. Using pressure and temperature controlled laminators with pre-coated materials adjusted for adhesion properties bubble free high quality multilayered bonded structures can be created. Fig. 17 shows the photopicture of a polymeric waveguide fanout circuit fabricated on a Kingston Fast Ethernet board. The key benefits of the lamination attribute include:

- Symmetric structures of nearly any desired thickness are routinely made that have submicron centering precision for buried waveguides.
- Controlled interdiffusion between initially unpolymerized layers obliterates any boundary and enhances bonding.
- Bonding of package layers that noted below through lamination using adhesion layers is critical to meet performance specifications.
- Large film structures can be easily processed producing large numbers of components or larger circuits.
- The entire packaged structure assembly is amenable to automated and high volume processing for low cost manufacture

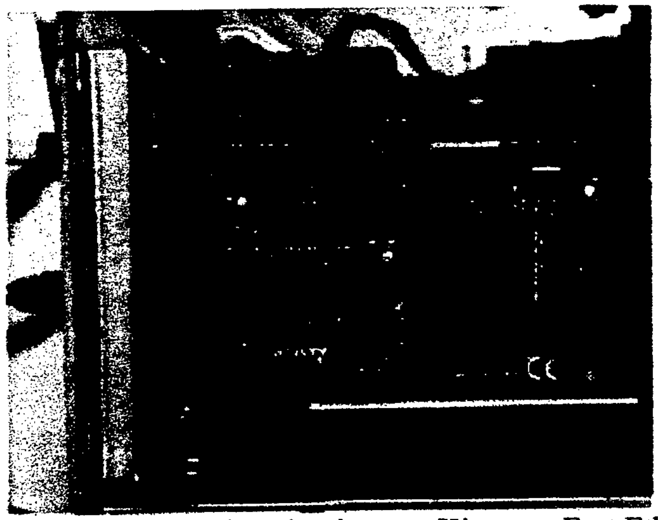


Fig. 17. Photo of an optical waveguide circuits on a Kingston Fast Ethernet board, based on laminated polymeric waveguide circuits developed at RRI.

(3) VLSI lithography technique

Due to the excellent repeatable results obtained during the Phase I research, the proposed ten-meter long polymeric waveguide circuits have been fabricated by using standard VLSI lithography techniques, which is the technology originally developed for microelectronics industries. Since the length of waveguides is defined by photolithography, the waveguide length can be precisely controlled and circled for more than 10 meters with accuracy in the sub-micron range. As a result, the proposed optical true-time-delay module based on polymeric waveguide circuits can provide 0.1 ps true-time-delay resolution over a 50 ns dynamic range. We have successfully fabricated a ten-meter long polymeric waveguide circuit using a VLSI lithography technique. Fig. 18 shows the ten-meter long polymeric waveguide circuit fabricated by this technique. The waveguide propagation loss is about 0.02 dB/cm measured at $\lambda = 1064$ nm.

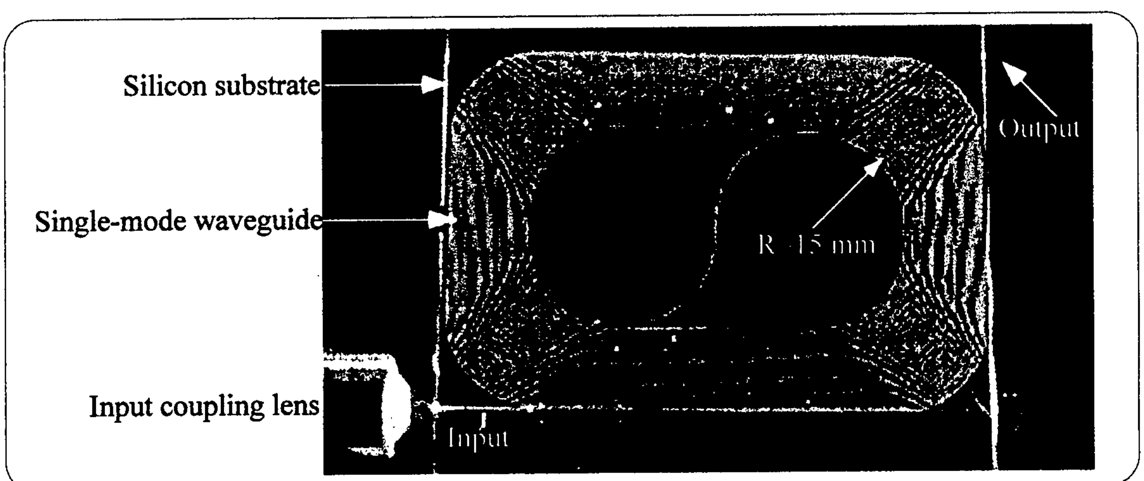
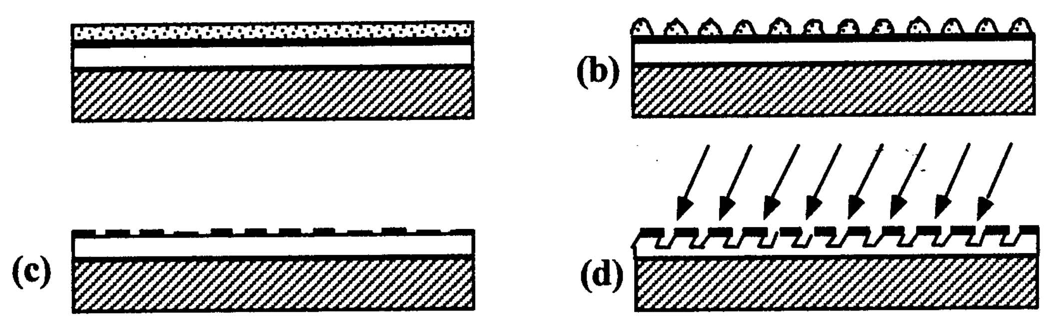


Fig. 18. Demonstration of a 10 m long polymer-based single-mode channel waveguide on a silicon substrate.

3.3.2 Fabrication of Tilted Waveguide Grating Coupler

To demonstrate optical TTD line with surface relief grating fanout, tilted waveguide grating couplers were fabricated on polymeric planar waveguide. The polymeric planar waveguide can be fabricated by spin-coating technique on any substrate of interest. For simplicity, glass substrate is selected where waveguide cladding is not required due to the low refractive index of glass. An A600 primer layer was spin-coated first on the substrate with a spin speed of 5000 rpm, and pre-baked at 90 °C for 60 seconds. The Amoco polyimide 9120D was then spin-coated on top of the primer layer with a speed of 2000 rpm. A final curing at 260 °C in nitrogen atmosphere was carried out for three hours. Typical thickness of the waveguide was 7 μm. The planar waveguide has also been successfully fabricated on silicon substrate by inserting a 9020D cladding layer between the 9120D guided layer and the silicon substrate.

We have chosen reactive ion etching (RIE) technique for tilted surface relief grating fabrication by taking the advantage of its highly directive capability. In order to fabricate the grating coupler by reactive ion etching (RIE) technique, a thin aluminum metal mask is needed on top of the polyimide-based planar guide. The schematic diagram for the fabrication process is shown in Fig. 19. First, a 500 Angstroms aluminum layer was coated on top of the waveguide by using electron beam evaporation, followed by a layer of 5206E photoresist with spin speed of 3000 rpm. The grating pattern was recorded by interfering two beams of He-Cd laser line at λ=442 nm on the photo resist.



(a) coating: polyimide, Al, photoresist, (b) hologram exposure, developing
(c) BCl3/SiCl4 RIE, (d) tilted oxygen RIE.

Fig. 22. Schematic diagram for fabricating the tilted grating on polyimide waveguide.

Fig. 20 illustrates the two-beam holographic recording setup. The cross-angle θ of the two interference beams is given by

$$\sin(\theta/2) = \left(\lambda/\Lambda\right) \qquad (13)$$

for a grating period of Λ. After the sample has been developed, a post-bake at 120 °C for 30 minutes was followed. To transfer the photoresist grating patterns to aluminum, we used RIE to etch the aluminum in the opening window of the photoresist pattern. The gases used were

$BCl_3/SiCl_4$ with a pressure of 20 millitorr. However, it was found that there were still some photoresist residuals in the grating groove, which could block the aluminum RIE process. In order to clean these residuals, an additional step of oxygen RIE etching was applied before removing the Al layer.

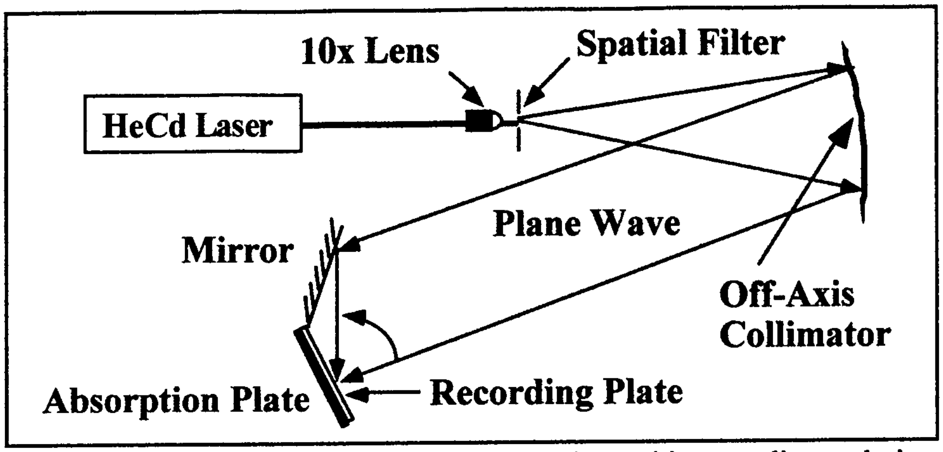


Fig. 20. Schematic diagram of two-beam holographic recording technique.

To form the tilted grating pattern on the polyimide waveguide, we used a RIE process with a low oxygen pressure of 10 millitorr to transfer the grating pattern on aluminum layer to the polyimide layer. In order to get the tilted profile, a Faraday cage [31] was used. The sample inside the cage was placed at a tilted angle of 40 degrees with respect to the incoming oxygen ions as shown in Fig. 21. The final step was to remove the aluminum mask by another RIE process. The waveguide tilted grating was successfully fabricated and the scanning electron microscope picture of shown in Fig. 22(b).

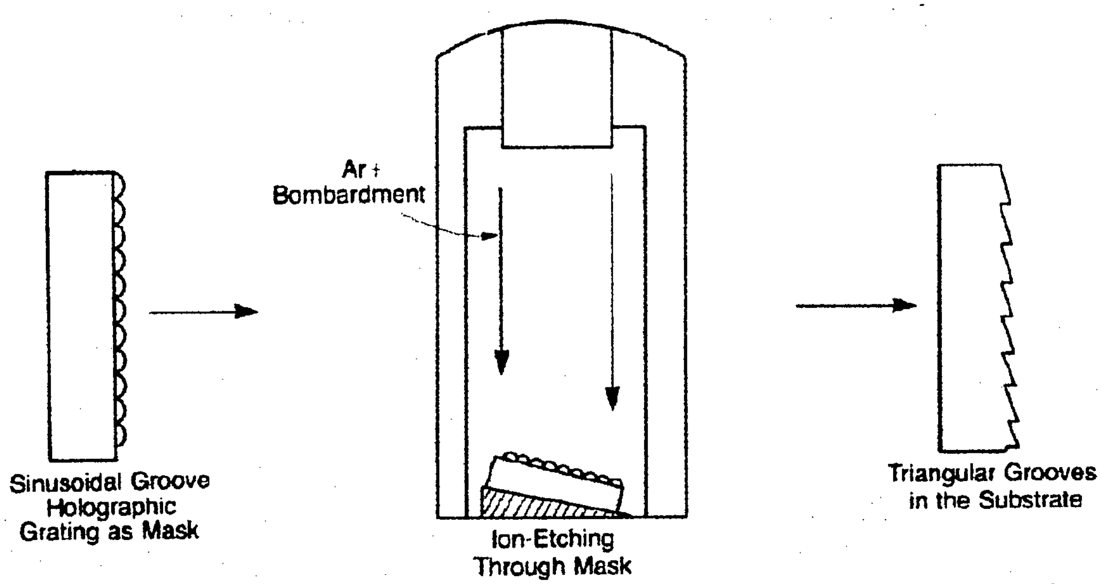


Fig. 21. Schematic diagram of tilted grating fabrication using directional RIE technique.

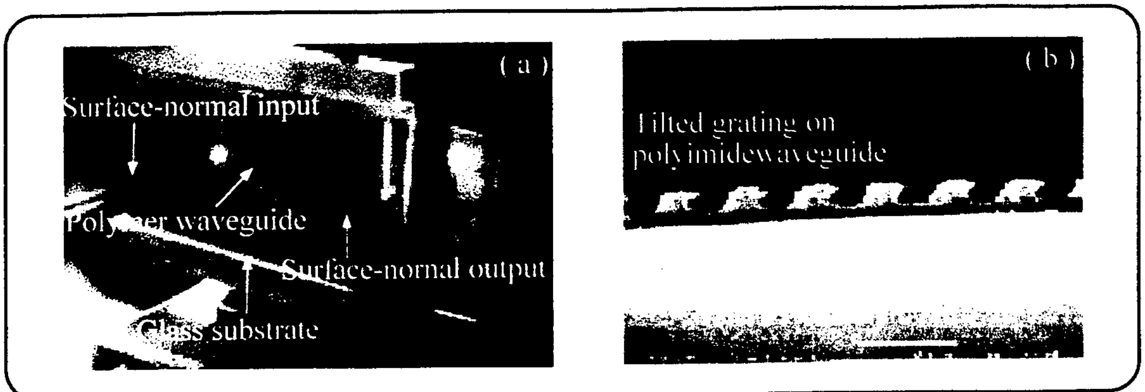


Fig. 22. Surface-normal waveguide fanouts using tilted waveguide grating couplers.

Fig. 22(a) shows the photopicture and the schematic diagram of coupling a laser beam into a polymeric channel waveguide and coupling light out of the waveguide surface-normally using the waveguide grating couplers. The polymeric channel waveguide is fabricated on a 8 cm long glass substrate, with waveguide thickness of 10 μm and width of 50 μm. The gratings are designed to surface-normally couple the laser beam out of the waveguide with an operating wavelength at 1060 nm. Seven fanout gratings are fabricated on top of the waveguide with 100 mm interaction length and 10 μm separation. In the experiment, a YAG laser with output wavelength of 1060 nm was employed. The seven optical fanouts are clearly observed. The output coupling efficiency is measured at 5%. Coupling efficiency can be well controlled by adjusting the grating depth. The non-blocking nature of the waveguide grating allows a large number of fanout along the waveguide propagation.

In the Phase I research, tilted gratings were successfully fabricated in polymeric waveguides by using RIE technique. The demonstrated grating couple shows the unique non-blocking optical coupling, which allows us to create a large number of fanouts along the waveguide propagation. In other wards, a large number of true-time-delays can be generated along the waveguide propagation with the delay time equal to the time of light flight along the waveguide circuit. The fabrication process established herein can be easily modified for other types of polymers.

3.3.3 Fabrication of high performance photodetectors

Selection of the appropriate photodiode depends on the wavelength and speed requirement of optical true-time-delay module. To date, most of the research on photodetectors and receiver OEICs for optical transmission has utilized III-V compounds because their materials characteristics yield higher speed and lower noise. However, Si integrated circuit technology is mature, compact, inexpensive, and has demonstrated high reliability. These characteristics make Si-based integrated circuit technology very attractive for making high-speed Si-based photodiodes. Unfortunately, the indirect bandgap of silicon results in a smaller absorption coefficient as compared to direct bandgap materials which, in turn, necessitates the use of a large absorption thickness in order to achieve high quantum efficiency. This tradeoff between bandwidth and responsivity can be circumvented with a resonant-cavity structure, which consists of a thin absorbing layer sandwiched between two dielectric mirrors. This approach effectively decouples the responsivity from the transit-time component of the bandwidth because the optical signal makes multiple passes across the thin absorbing layer inside the microcavity. Previously we have used this approach to demonstrate a Si resonant-cavity photodiode that utilized a GeSi/Si mirror. This photodiode achieved very high speed (f_{3dB} > 15 GHz) and good quantum efficiency (~ 65%).

We have fabricated Ge_xSi_{1-x}/Si Bragg reflector mirrors that have achieved a reflectivity > 90%, in collaboration with Prof. Ray T. Chen in the Microelectronics Research Center of the University of Texas at Austin. The Ge_xSi_{1-x}/Si Bragg reflector mirrors have been successfully incorporated into Si-based resonant-cavity photodiodes[10]. Fig. 23 shows the schematic cross-section of the Si/SiO_2 resonant-cavity photodiode fabricated. These devices have exhibited the following characteristics:

- High external quantum efficiency: 67%
- Low dark current: < 10 nA at 10 V.
- Avalanche gains in excess of 20 for very low bias voltages (< 20 V).
- Ultra high bandwidths: 15 GHz.

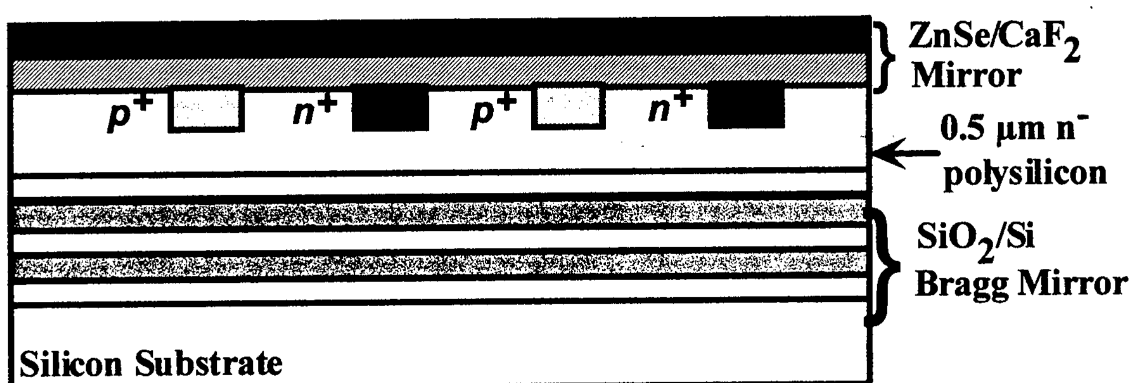


Fig. 23. Schematic cross-section of the Si/SiO_2 resonant-cavity photodiode.

The frequency response of the Si/SiO_2 photodiodes was determined by analyzing the photocurrent spectrum produced by excitation with a mode-locked Ti:sapphire laser. The laser was tuned to a response peak of the photodiode. The pulse width of the laser was <200 fs. A 12µm x 18µm diode was measured on wafer using microwave probes. This measurement technique produces a series of spikes separated by the pulse repetition rate (75 MHz), the envelope of which gives the photodiode response. Fig. 24 shows the 11 GHz bandwidth of the photodiode fabricated.

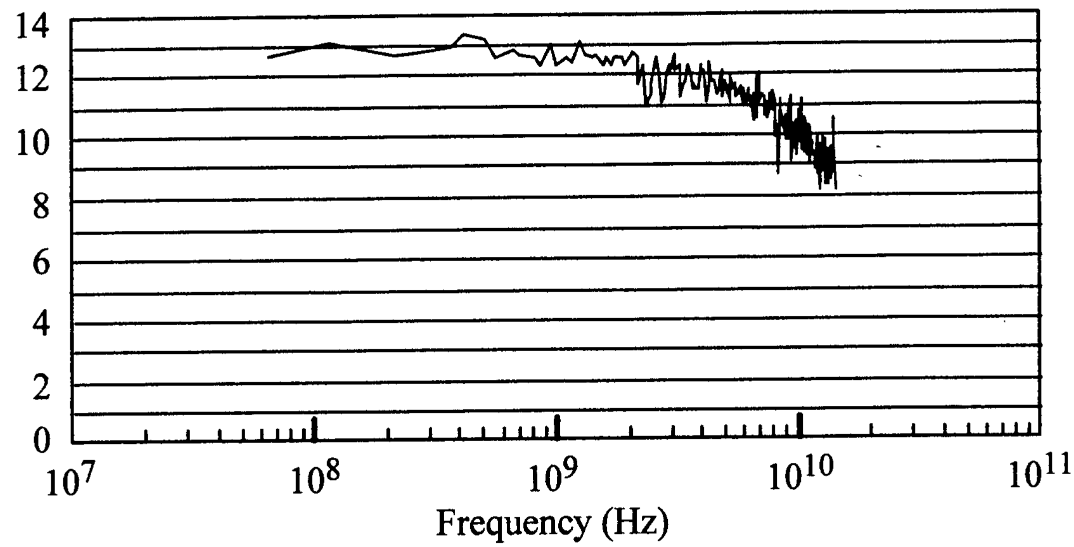


Fig. 24. Frequency response of Si/SiO_2 resonant-cavity photodiode.

Conventional highs-peed InGaAs detector and GaAs amplifiers have been manufactured as discrete components, and subsequently wire bonded together using hybrid technology, which gives rise to several drawbacks to include (a) increased labor, low yield, low reliability, and increase parasitic losses. These problems become worse at higher frequencies.

Our industry collaborator-Discovery Semiconductor has developed a unique integrated dual depletion InGaAs photodetecor/InP p-HEMT amplifier, which not only eliminates the drawbacks of the hybrid method, but also produces higher speed transistors owing to the use of InP as the active material. The frequency response of the photodetector is tested and shown in Fig. 25. This frequency response indicates that the ripple factor is less than 1 dB for a wideband operation from DC to 45 GHz. Fig. 26 shows the electrical block diagram of the photoreceiver and its circuit layout. This photoreceiver exhibit 11 dB of gain across the RF spectrum from DC to 20 GHz. This photoreceiver has been employed in our optical waveguide true-time-delay module, capable of providing 5 mW microwave power at the output end of the photoreceiver. Discovery Semiconductor will further improve their device performance up to 40 GHz to meet our broadband optical TTD line requirements.

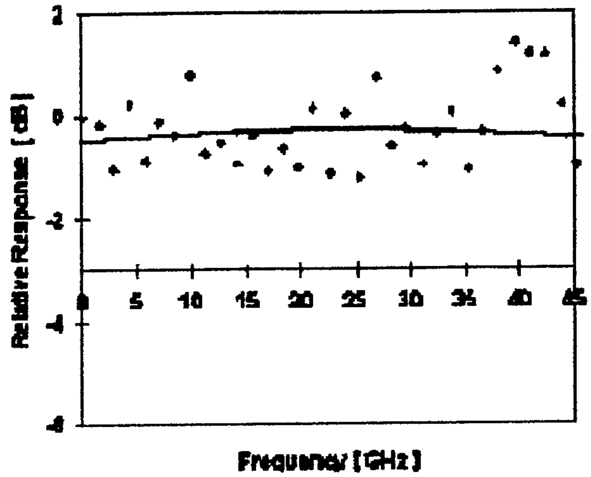


Fig. 25. Frequency response of Discovery's InGaAs PIN photodetectors.

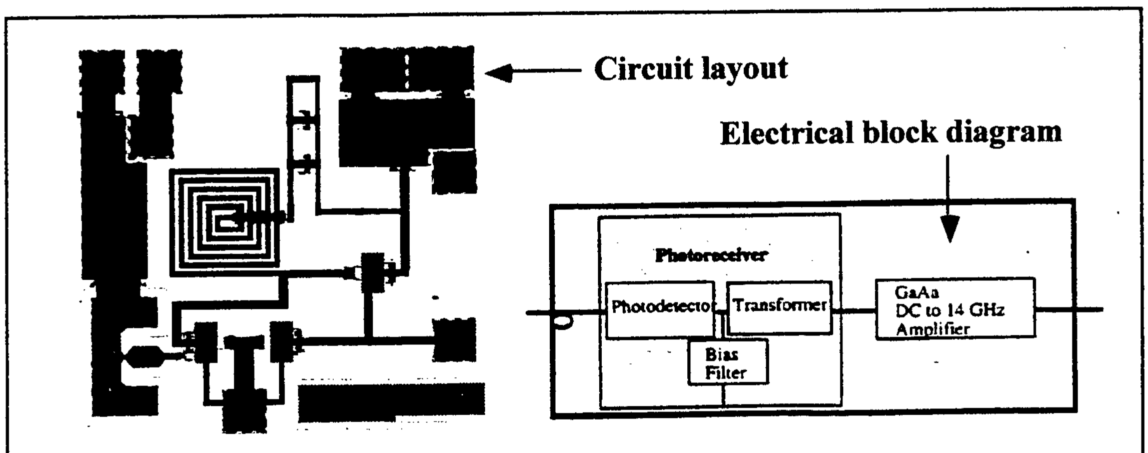


Fig. 26. Electrical block diagram and circuit layout of the Discovery's monolithically integrated InGaAs PIN amplifier photoreceiver OEIC.

4.0 FUTURE APLICATIONS

Our Phase I effort has demonstrated the feasibility and emphasized the advantages of using compact photonic polymer-based waveguide circuits to enhance the performance of optical true-time-delay lines. At the end of Phase I period, three basic components including design of a compact optical true-time-delay network based on ultra-low-loss polymer waveguide circuits, the technology of fabricating ultra-low-loss polymer-based waveguides, and high-performance surface-normal waveguide gratings, have been established. These accomplishments provide a technical foundation for the design and fabrication of a production prototype detector-switched multi-link optical true-time-delay line, which can be realized in a Phase II stage. The prototype of Phase II research and development shall be easily transferable to industry for further system integration. To summarize, our completed Phase I research and future Phase II effort will build a solid technical foundation for a pre-product three-dimensional true-time-delay module. This prototype module will result in a phased array antenna that has low cost, wide coverage, flexible frequency change, multiple beams over wide bands, high transmission capacity, and multiple link ability.

The ultra long polymer-based waveguide is one of the most important building blocks for constructing optical true-time-delay line architectures[2-6]. Fig. 27 shows the product oriented research and development currently being carried in Radiant Research Inc. In this architecture, the optical signal is optionally routed through N waveguide segments whose lengths increase successively by a power of 2. Since each switch allows the signal to either connect or bypass a waveguide segment, a delay T may be inserted which can take any value, in increments of $\Delta\tau$, up to the maximum value $T_{max}=(2^N-1)(\Delta\tau)$. The ultra-low-loss polymer-based waveguide will certainly improve the dynamic range of this product.

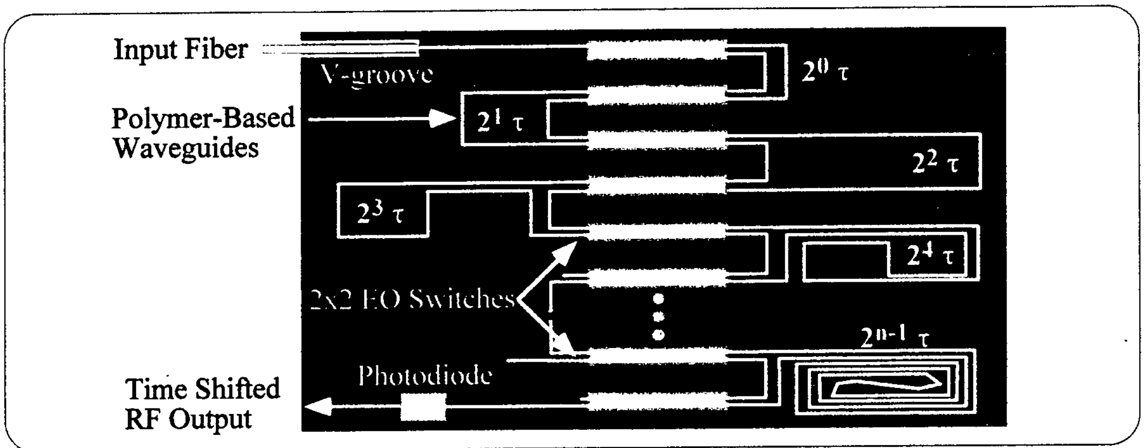


Fig. 27. Programmable optical binary true-time-delay generator using integrated polymer-based waveguides and 2x2 switches.

Another product oriented research, where the fabricated ultra-low-loss polymer circuits will find an important application, is guide-wave optical clock signal distribution for Cray T-90 supercomputer[10,12,32]. For current supercomputer systems, such as Cray T-90, it is extremely difficult to obtain high-speed (>500 MHz) clock signal distribution using electrical interconnections due to large number of fanouts and long interconnection length (>15 cm). Radiant Research, Inc. has been funded by Cray Research, Inc. for last two years, to demonstrate the feasibility of realizing a board-level optical clock signal distribution network based on optical waveguide H-tree. Fig. 28 shows the polymer-based waveguide H-tree developed at RRI, which is capable of providing optoelectronic clock signal distribution to more than 96 processors at the speed of 1-GHz[32]. Due to the nature of large optical fanout, this clock speed is currently limited by the power budget of the high-speed photodetector. To improve the clock speed, the photodetector requires more incident power at each fanout. The proposed ultra-low-loss polymer waveguide with optical amplification will certainly be one of the most promising technology.

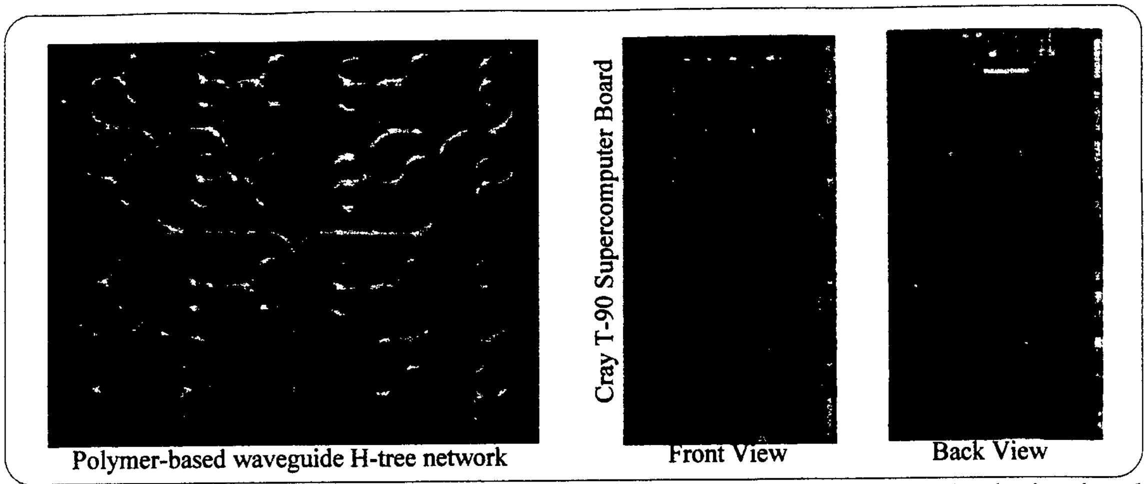


Fig. 28. Photograph of polymer-based waveguide H-tree for optical clock signal distribution in Cray T-90 supercomputer. The pictures of T-90 board are also given.

5.0 CONCLUSION

We have successfully demonstrated a photonic waveguide based true-time-delay line by using a polymeric waveguide in conjunction with wavelength selective grating couplers. This research provides a conceptual basis for developing compact optical true-time-delay technology for future generation of phased array antennas. The technology demonstrated includes fabrication techniques for ultralong polymeric waveguides, tilted surface normal grating couplers, and fast switched photodiode detector arrays. Such a highly condensed delay structure in addition to WDM technique incorporated allow ultra broad bandwidth operation of the TTD line developed. The polymeric waveguide of ultra-long length and its photolithographically defined grating structure provide large dynamic range of 50 ns as well as a fine true-time-delay resolution of 0.1 ps. The waveguide grating coupler is ideal for WDM operation where different optical wavelengths can be fanout at different locations with different grating periods fabricated. The optical crosstalk was determined at –28 dB with channel separation at 200 GHz in our WDM experiment. The crosstalk could be further reduced using larger channel separation.

The accomplishments of Phase I research include both concept development and prove and both polymer and photonic technology development. The primary objectives of the Phase I work were (1) to demonstrate the feasibility and advantages of a detector-switched optical TTD line based ultra-long polymeric waveguide circuits, (2) to demonstrate a photonic polymer for enhancing the performance of optical true-time-delay lines, which can provide optical amplification along the waveguide propagation, and (3) to establish the technical foundation for fabricating photonic polymer waveguides with a large number of surface-normal fanout gratings over a long distance. By accomplishing all tasks of the proposed Phase I effort, we have established the theoretical and technical foundation for realizing a compact detector-switched optical TTD module based ultra-long polymeric waveguide circuits. Upon the successful completion of the above objectives in Phase I, the feasibility of an innovative concept of photonic phased array antenna based on detector-switched optical TTD lines has been demonstrated. Crucial technologies for producing a compact detector-switched twin-beam optical true-time-delay line based on photonic polymer waveguide circuits have been established. A ten-meter long polymeric waveguide with very low propagation loss (0.02dB/cm) is demonstrated for the first time. We have successful realized a small-scale photonic waveguide delay line system before the end of Phase I. The performed experimental demonstrations include:

(1) Ten meter long polymeric waveguide circuits with low waveguide loss (0.02 dB/cm),

(2) Surface normal waveguide gratings for optical true-time-delay fanouts,

(3) Optical heterodyne generation of RF signals in the range of 11-50 GHz,

(4) 50-picosecond step optical true-time delay measurement,

(5) Fabrication of high-speed photodetector with amplifiers,

(6) WDM operation for 100 GHz wideband photonic waveguide circuits,

From these successful demonstrations, an airborne phased array antenna based on a novel miniaturized optical true-time-delay module can be designed and analyzed for future applications. Section 4 details these important technical achievements. In summary, we have established in Phase I the theoretical and technical foundation for realizing a detector-switched optical TTD line based ultra-long polymeric waveguide circuit. At present, all the building blocks essential for the fabrication and modeling of this innovative technological module are available. The achieved results strongly encourage us to pursue further R&D effort in Phase II, aimed at the fabrication of a prototype high performance detector-switched optical TTD line module which is Integra table to an advanced Photonic Phased Array Antenna system.

The study accomplished in this Phase I period brings together different micromachined components to achieve optical true-time-delay in a compact, efficient, and low cost fashion. Such a hybrid integration to photonic devices, such as laser diodes and photodetectors, eliminates the most difficult optoelectronic packaging problem in developing advanced photonic phased array antennas. This integrated approach not only reduces the cost associated with optoelectronic packaging, but also reduces the system payload with an improved reliability for airborne applications. At present day, the all building block essential for the fabrication of wideband phased array antenna are getting available, while the electrically-switched optical polymeric waveguide delay lines certainly present one of the very promising results in this field. In conclusion, polymeric waveguide technology, including ultra-low loss polymeric waveguides, efficient waveguide grating couplers, and optical waveguide amplifiers, offers an unique hybrid integration in realizing advanced photonic phased array antennas based on optical true-time-delays.

6.0 REFERENCES

1. Selected Papers on Photonic Control Systems for Phased Array Antennas, 1997, SPIE Milestone Series Vol. MS 136, Nabeel A. Riza, Ed.
2. The fifth annual ARPA symposium on photonic systems for antenna applications, 1995.
3. John E. Midwinter, Photonics in Switching (Academic Press, Boston, 1993).
4. Henry Zmuda, and Edward N. Toughlian, Photonic Aspects of Modern Radar, (Artect House, Inc., Norwood MA 1994), Chapter 13, 17.
5. K. Horikawa, I. Ogawa, T. Kitoh, and Hiroyo, Ogawa, "Photonic integrated beam forming and steering network using switched true-time-delay silica-based waveguide circuits," IEICE Trans. Electron., vol. E97-C, no. 1, pp. 74-79, 1996.
6. L. Xu, R. Taylor and S. R. Forrest, "True time-delay phased-array antenna feed system based on optical heterodyne techniques," IEEE Photon. Technol. Lett., vol. 8, no. 1, pp. 160-162, 1996.
7. Henry Zmuda, Richard A. Soref, Paul Payson, Steven Johns, and Edward N. Toughlian, "Photonic beamformer for phased array antennas using a fiber grating prism," IEEE Photon. Technol. Lett., vol. 9, no. 2, pp. 241-243, 1997.
8. K. Horikawa, I. Ogawa, T. Kitoh, and Hiroyo, Ogawa, "Photonic integrated beam forming and steering network using switched true-time-delay solica-based waveguide circuits," IEICE Trans. Electron., vol. E97-C, no. 1, pp. 74-79, 1996.
9. **Suning Tang**, Ting Li, F. Li, Michael Dubinovsky, Randy Wickman and Ray T. Chen, "Board-level optical clock signal distribution based on guided-wave optical interconnects in conjunction with waveguide hologram," Proc. SPIE, vol. 2891, pp. 111-117, 1996.
10. Ray T. Chen, **Suning Tang**, F. Li, L. Wu, M. Dubinovsky, J. Qi, C. Schow, J. Campbell, R. Wickman, "Si CMOS process compatible guided wave optical interconnects for optical clock signal distribution," Invited Paper in IEEE MPPOI'97, vol. 4, pp. 10-24, 1997.
11. **Suning Tang**, Rob Mayer, Maggie M. Li, and Ray T. Chen, "A novel polymer waveguide wavelength-division-demultiplexer with optical in-plane to surface-normal conversion," IEEE Photon. Technol. Lett., vol. 7, no. 8, pp. 908-910, 1995.
12. **Suning Tang** and Ray T. Chen, "Intra-Multi-Chip-Module (MCM) optical clock signal distribution," Optics & Phonics News, vol. 5, no. 12, pp. 41-42, December, 1994.
13. Ray T. Chen, Maggie M. Li, **Suning Tang** and Dave Gerold, "Nd^{3+}-Doped graded index single-mode polymer waveguide amplifier working at 1.06 and 1.32 mm," Proc. SPIE, Vol. 2042, pp. 462-463, 1993.
14. Gerhard A. Koepf, "Optical processor for Phased-Array Antenna beam formation", Proc. SPIE V. 477, pp. 75-81, 1984.
15. A. Daryoush, P. Herczfeld, V. Contarino, A. Rosen, Z. Turski, and P.Wahi, "Optical beam control of mm-Wave phased array antennas for communications", Microwave Journal, Vol. 30(3), pp. 97, 98, 100, 102-104, 1987.
16. Neelam Gupta, George Simonis, and Paul Ashley, "Lithium niobate integrated-optics demonstration of optical control of microwaves", Optoelectronic Signal Processing for Phased Array Antennas II, Proc. SPIE V. 1217, pp. 92-100, 1990.
17. Nabeel A. Riza, "Liquid crystal-based optical control of phased array antennas", Journal of Lightwave Tech. Vol. 10(12), pp. 1974-1984, 1992.

18. R. D. Esman, L. Goldberg, and J. F. Weller, "Optical phase control of an optically injection-locked FET Microwave Oscillator", Transactions on Microwave Theory and Techniques, Vol. 37(10), pp. 1512-1518, 1989.
19. W. Wang, Y. Shi, W. Lin, and J. H. Bechtel, "Waveguide binary photonic true-time-delay lines using polymer integrated switches and waveguide delays", Photonics and Radio Frequency, Proc. SPIE Vol. 2844, 200-211, 1996.
20. Eli Brookner, Practical Phased-Array antenna systems, Artech house, Boston, 1991.
21. Suning Tang, L. Wu, Z. Fu, D. An, Z. Han, and Ray T. Chen, "Polymer-Based Optical Waveguide Circuits for Photonic Phased Array Antennas", Proc. SPIE, vol. 3632, pp. 250-261, 1999.
22. J. J. O'Reilly and P. M. Lane, "Fiber-supported optical generation and delivery of 60 GHz signals", Electron, Lett., 30, 1329, 1994.
23. G. J. Simonis, and K. G. Purchase, "Optical generation, distribution, and control of microwaves using laser heterodyne", IEEE Trans. Microwave Theory Tech., vol. 38, p. 667, 1990.
24. J. B. Georges, M.-H. Kiang, K. Hepell, M. Sayed, and K. Y. Lau, "optical transmission of narrow-band millimeter-wave signals by resonant modulation of monolithic semiconductor lasers", IEEE Photon. Tech. Lett., vol. 6, p. 568, 1994.
25. C. R. Lima, D. Wake, and P. A. Davis, "compact optical millimeter-wave source using a dual-mode semiconductor laser", Electron. Lett., vol. 31, p. 364, 1995.
26. K. Kitayama, "Highly stabilized millimeter-wave generation by using fiber-optic frequency-tunable comb generator", IEEE J. Lightwave Tech., vol. 15, p. 883, 1997
27. Ray T. Chen, "Polymer-based photonic integrated circuits," (Invited review paper), Optics and Laser Technology, vol. 25, pp. 347-365, 1993.
28. Ray T. Chen, **Suning Tang**, Tomasz Jannson and Joanna Jannson, "45-cm long compress-molded polymer-based optical waveguide bus," Appl. Phys. Lett., vol. 63, no. 8, pp. 1032-1034, 1993.
29. **Suning Tang**, Ray T. Chen and Mark A. Peskin, "Packing density and interconnection length of a highly parallel optical interconnect using polymer-based, single-mode waveguide arrays," Opt. Eng., vol. 33, no. 5, pp. 1581-1586, 1994.
30. **Suning Tang**, et. al., "Compression-molded three-dimensional tapered optical polymeric waveguides for optoelectronic packaging," SPIE, vol. 3005, pp. 202-211, 1997, and IEEE Photon. Technol. Lett., vol. 9, no. 12, pp. 1601-1603, 1997.
31. G.D.Boyd, L.A.Coldren, F.G.Storz, "Directional reactive ion etching at oblique angles", Appl. Phys. Lett., vol. 36, no. 7, pp. 583-585, 1980.
32. **Suning Tang**, Ting Li, F. Li, Micheal Dubinovsky, Randy Wickman and Ray T. Chen, "1-GHz Clock Signal Distribution for Multi- processor Super Computers," MPPOI'96, Hawaii, pp. 186-191 1996.