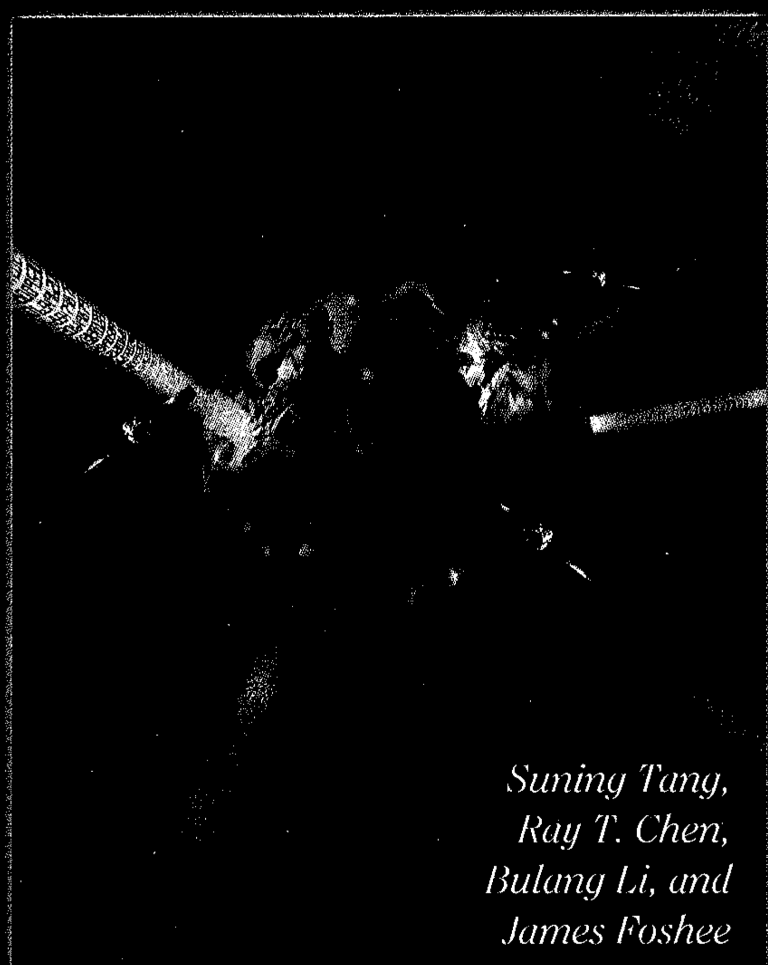
Waveguides take to the Sky

Polymeric Waveguide Circuits for Airborne Photonic Phased-Array Antennas Enable Communication Without Boundaries



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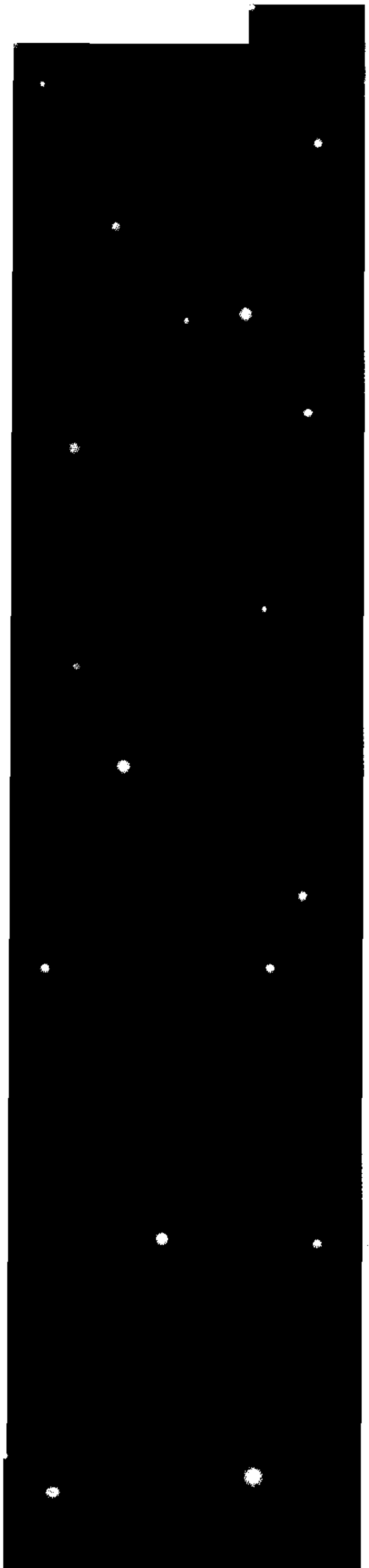


The arrival of the new millennium is setting the dawn of a new age—the information age. As the worldwide communications network is built to connect the world's populous through the Internet, fiber-optics are reviving the backbone of the telecommunications infrastructure. This infrastructure provides a network of wirelines to individuals and business in the world's well-developed or populated areas. Looking at another dimension, wireless communications through satellite constellations extend our communications capability into the sky to reach the remote areas that the ground networks cannot cover. This airborne dimension of networks is becoming increasingly important due not only to its complementary role to the existing wireline or future all-fiber-optic ground networks but also to its promised advantage of "anywhere accessibility."

Phased-array antennas based on optical true-time-delay (TTD) lines can quickly track several satellites using the slightly different signals received by the array of antennas without physically moving. This article provides an overview of recent developments in wireless and airborne communications technology and presents the authors' research activities in invoking advanced polymeric waveguide circuits for building key blocks of wide-bandwidth phased-array antenna systems. The advantages of polymeric waveguides for microwave signal distribution are also explored.

Satellite Constellations

The wireless communications network is traditionally employed for military purposes and commercial telephone and video applications, and it has mostly relied on geosynchronous equatorial orbit (GEO) satellites. The geosynchronous satellites are fixed at a distance of 22,300 miles away from the Earth's equator, which generates a 0.24 second round trip. Due to this serious latency problem, along with limited bandwidth due to the limited number of satellites in the GEO constellation, both military and commercial networks are concentrating on building low-earth-orbit (LEO) satellite constellations (500-1000 miles from the Earth).

The LEO satellite constellations will have a large number of satellites and at least 20 times lower latency compared to the GEO constellation. The satellites in the LEO constellation will have built-in links that allow them to communicate with each other in the constellation and with airplanes or ground stations, forming an "Internet-in-the-Sky." The large number of satellites in the constellation will allow airplanes in the sky and individuals on the ground to have a line of sight anytime and anywhere.

Different from geostationary satellites, the LEO satellites will be circling the Earth at a synchronous speed between the satellites, providing seamless coverage to any location on the ground and above. One notably ambitious LEO satellite system to be launched is the Teledesic Satellite Constellation, which consists of more than 280 satellites divided into 12 planes orbiting around the Earth. Teledesic will operate in a portion of the high-frequency Ka-band (28.6-29.1 GHz uplink and 18.8-19.3 GHz downlink). The Teledesic Network's low orbit eliminates the long signal delay experienced in communications through traditional geostationary satellites and enables the use of small, low-power terminals and antennas.

Phased-array antennas based on optical TTD lines can track several satellites using the slightly different signals received by the array of antennas, without physically moving, which reduces wear and tear, among other advantages. The problem of keeping a link active when the targeted satellite disappears every half-hour is solved by keeping at least two satellites in view at all times. The phased-array antenna is aware of all the satellite positions and starts a new link before it severs the one to the setting satellite. It is an ideal airborne technology for utilizing an LEO satellite constellation as wideband RF data links in situations where a conventional high-bandwidth infrastructure is not achievable.

Phased-Array Antennas Based on Optical True-Time-Delay Technology

To transfer information from ground stations to satellites (uplink), from satellites to satellites (interlink), and from satellites to ground stations (downlink), the phased-array antenna is currently the technology of choice to 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 devices of such radar systems are solid-state devices configured as discrete devices on printed-circuit boards, integrated circuits on silicon substrates, hybrid integrated circuits, and monolithic microwave integrated circuits, which are small, lightweight, 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 TTD techniques have to be employed for wideband applications.

We present a new approach for developing wideband phased-array antennas using polymeric waveguide technologies.

The phased-array antennas 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 of radiating elements with individual phase control, the far-field pattern along the direction of Φ can be expressed as [1]:

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

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 the 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 example, to point the beam at an angle Φ_0, Ψ_n is set to the following value:

$$\psi_n = -nk_m\Lambda\sin\Phi_0 . \tag{2}$$

Differentiating Eq. (2), we have

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

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, the so-called "beam squint," increases dramatically as Φ_0 increases, which sets the limitation on antenna bandwidth.

In order to obtain the ultra-wide bandwidth, it is necessary to implement an optical TTD steering technique such that the far-field pattern is independent of the microwave frequency [2]. In the approach of optical TTD, 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

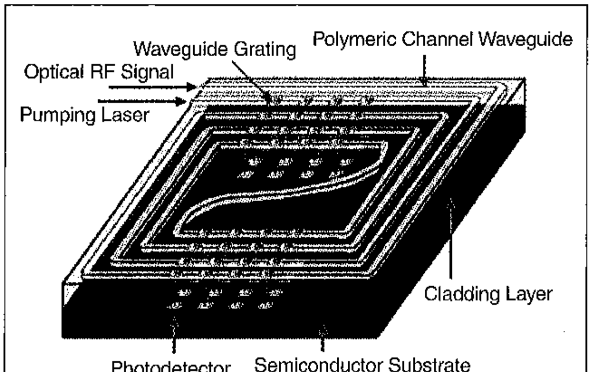
$$t_n(\Phi_0) = (n\Lambda\sin\Phi_0)/c \tag{4}$$

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

$$\psi_n = -\omega_m t_n(\Phi_0). \tag{5}$$

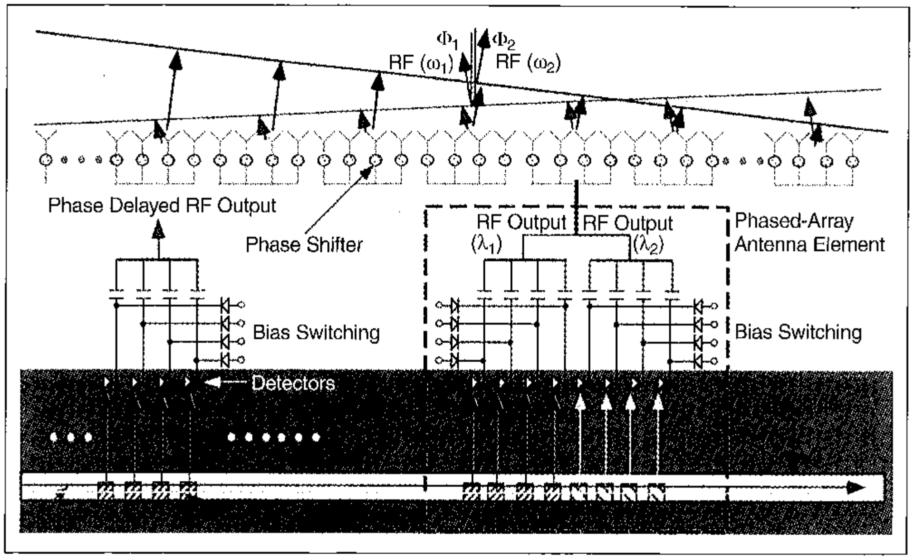
With such a delay setup, when the phase term $nk_m\Lambda\sin\Phi$ inside Eq. (1) is changed due to frequency "hopping," the phase term ψ_n will change accordingly to compensate for the change such that the sum of the two remains unchanged. Thus, constructive interference can be obtained in the direction Φ_0 at all frequencies. In other words, the elemental vector summation in the receiving mode or in the transmit mode is independent of frequency, which is crucial for ultra-wideband operation for future phased-array antennas.

The existing phased-array antenna technologies include microstrip reflecting array antennas with mechanical phasing [3],



1. Schematic diagram of the compact multilink optical TTD line based on polymeric waveguide circuits.

fiber-grating prisms [4], and thermo-optically switched silica-based waveguide circuits [5]. These attempts have demonstrated the low weight potential and some good performance characteristics. The mechanical phased microstrip antennas do not need expensive beamforming transmission-line networks and/or phase-shifting circuits. The beam steering is provided by the mechanical rotation of each antenna element. In fiber-Bragg grating prism technology, high-performance reflection gratings can be easily fabricated in ultra-low-loss optical fibers, but this requires very expensive, fast wavelength-tunable laser diodes. The thermo-optically-switched silica-based waveguide circuit offers excellent delay-time control in a compact structure where the length of waveguide is defined by photolithography.



2. Electrical diagram of a detector-switched optical waveguide TTD line for photonic phased-array antennas.

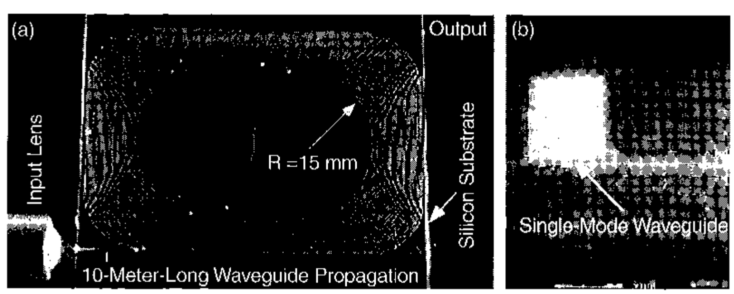
There are several severe problems involved with these existing approaches. For example, they are incapable of providing high-speed beam steering due to the speed limitation of mechanical driving motors, wavelength-tunable laser diodes, and/or 2 × 2 thermo-optic switches. The existing approaches also require very expensive components such as miniaturized motors, wavelength-tunable laser diodes, and 2 × 2 thermo-optic switches, which make the system impractical for commercial applications. The techniques for improving these existing approaches demonstrated so far generally add to system complexity, employ very expensive devices, and/or require extremely difficult fabrication processes.

Application of Polymeric Waveguide Circuits

Because polymeric waveguide technology is conceptually hybrid, it opens up the possibility for a large-scale optoelectronic integration on any substrate in a cost-effective manner. In this article, we present a new approach for developing wideband phased-array antennas using polymeric waveguide technologies [6]. In this approach, optical TTD lines are made out of photonic polymeric waveguide circuits and electrically switched high-speed photodetectors, as shown in Fig. 1. This optical TTD line uses an ultra-long photonic polymeric channel waveguide circuit on a semiconductor substrate, where a high-speed photodetector array is prefabricated. The photonic polymeric waveguide circuits consist of (1) polymeric channel waveguides, (2) waveguide grating couplers, and (3) waveguide amplifiers. Such a polymeric waveguide circuit is capable of providing optical TTDs from 1 ps to 50 ns for wideband multiple communication links in a compact, miniaturized scheme.

The optical amplification along the waveguide propagation compensates for the optical loss due to the waveguide propagation loss and grating fanout loss. An optical heterodyne technique is used for generating an optical RF carrier by employing two coherent laser diodes with slightly different wavelengths. A large number of TTD combinations can be provided for the phased-array antenna simultaneously by electronically switching the photodetector array 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 2 × 2 waveguide switches. Unlike any conventional approach where one TTD line can provide only one delay signal at a time, this TTD module is capable of generating all required optical TTD signals simultaneously to all antenna elements. Note that the bandwidth of this approach is currently limited by the bandwidth of the photodetectors at 60 GHz.

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 MSM

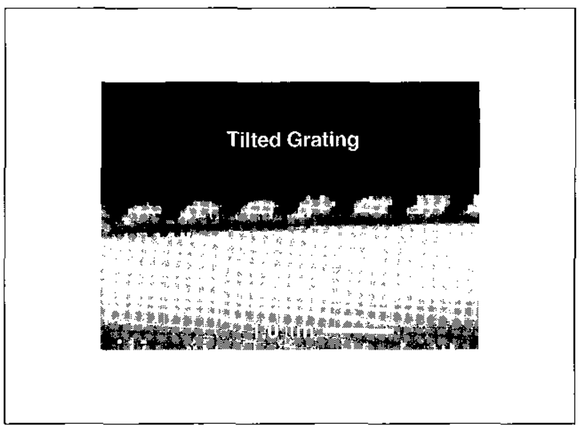


3. Photographs of (a) the 10-meter-long polymeric waveguide circuit and (b) the waveguide cross section.

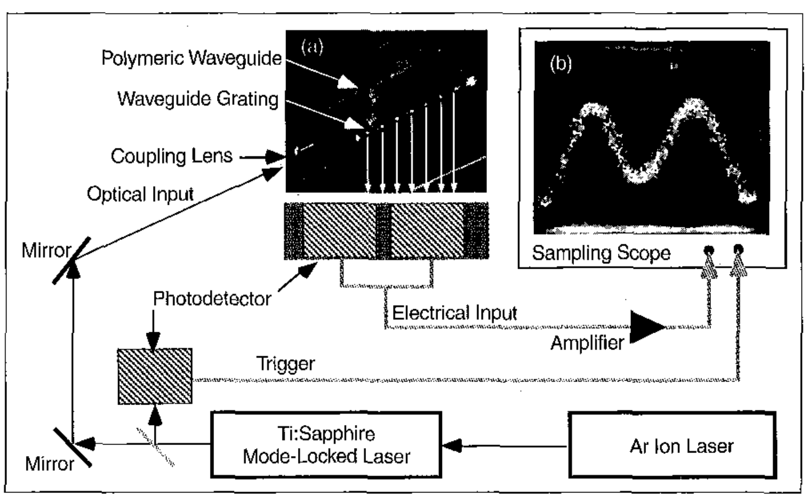
photodetectors have a typical bias voltage of less than 10 V with bandwidths up to 60 GHz. Figure 2 shows the electrical diagram of a detector-switched optical TTD module. Such a hybrid integration of detectors in the optical waveguides eliminates the most difficult optoelectronic-packaging problem associated with the delicate fiber-detector interface and/or fiber-switch interface. It reduces not only the cost associated with optoelectronic packaging but also the system payload, with an improved reliability for airborne applications. The TTDs for multiple communication links can be simply provided by employing multiple RF-modulated beams at different wavelengths over the same delay line based on the wavelength-division-multiplexing technique indicated in Fig. 2.

Using photonic phased-array antennas in conjunction with orbiting satellites is an ideal method to bring high-bandwidth information to any aircraft in any location.

The unique optical amplification feature of photonic polymers allows us to fabricate an ultra-long optical channel waveguide with a large number of fanout gratings [7]. The optical propagation loss and fanout loss is compensated by the optical gain throughout the waveguide delay line. As a result, a large number of time delays can be obtained by using a single laser diode for advanced photonic radar systems that often have 10^3 to 10^5 antenna elements. The optical gain is provided within the photonic polymeric waveguide doped with rare-earth ions, such as Nd^{3+}, and pumped by a third laser (λ_3) from another end of the waveguide circuit. In order to obtain uniform fanout, the optical gain in the waveguide section between two fanout gratings can be engineered to exactly compensate for the sum of the waveguide propagation loss and optical fanout loss. 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 the waveguide is defined by photolithography, the optical polymeric waveguide delay lines can provide a 0.1 ps TTD 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.



4. Scanning electron microscope picture of tilted waveguide gratings.



5. Schematic diagram for measuring the optical true-time-delays using a femtosecond Ti:Sapphire laser system.

10-Meter-Long Polymeric Channel Waveguide

In order to realize a high-performance phased-array antenna, the optical polymeric waveguide may need to be over 10 meters long to provide sufficient optical TTD. For a phased-array antenna with element-to-element spacing of $d = \lambda/2$, where λ is the wavelength of the RF radiation, the maximum possible delay time is equal to [11]:

$$T_{i\,\max} = i\lambda \sin\theta_m / 2c \quad i = 1,2,3,\ldots,K \tag{6}$$

where θ_m is the maximum scan angle, c is the speed of light, and K is the number of elements of a phased-array antenna. The minimum delay corresponding to the antenna's angular resolution θ_R is

$$T_{i\,\min} = i\lambda \sin\theta_R / 2c\,. \tag{7}$$

Eqs. (6) and (7) determine the $T_{i\max}$ and $T_{i\min}$ and the total number R of different delays required for steering the antenna over θ_m with resolution θ_R.

For example, for the designed antenna operating at $f = 11$ GHz (or λ = 27.3 mm), with $\theta_m = 45°$, $\theta_R = 0.7°$, a six-bit delay line ($R = 2^6 = 64$) is required with $T_{\max}$ = 2.06 ns and $T_{\min}$ =

35.6 ps. These correspond to a maximum delay line of $L_{max} = T_{max}c/n$ = 42 cm, and a minimum delay step of $L_{min} = T_{min} c/n$ = 7.1 mm, respectively. Here n = 1.5 is the optical refractive index of the polymeric waveguide. The antenna element separation is $d = \lambda/2$ = 13.65 mm. The required dimension of the two-dimensional phased-array antenna is $S = (dR)^2 = (13.65 \times 64)^2 = 873.6 \times 873.6$ mm^2. As many as 64×64 = 4096 antenna elements may be required. Such a two-dimensional phased-array antenna can electronically scan in two dimensions and can cover at least nine satellites at all times in all locations.

This integrated approach reduces the system payload with improved reliability for airborne applications.

Due to the excellent repeatable results, standard VLSI lithography techniques are selected for fabrication of the 10-meter-long polymeric waveguide circuits. 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 submicron range. As a result, the polymeric waveguide delay circuits can be fabricated with a 0.1 ps TTD resolution over a 50 ns dynamic range. We have successfully fabricated a 10-meter-long polymeric waveguide circuit using VLSI lithography techniques. Figure 3 shows the 10-meter-long polymeric channel waveguide circuit with a waveguide dimension of 5 µm × 5 µm. The waveguide propagation loss is about 0.02 dB/cm measured at λ = 1064 nm. Ultra-low-loss optical polyimides have been employed for the waveguide fabrication. These polyimides have shown excellent optical transmission characteristics with good thermal and chemical stability over time and temperature. They have been proven to be silicon CMOS-process compatible.

Fabrication of Tilted Waveguide Grating Couplers

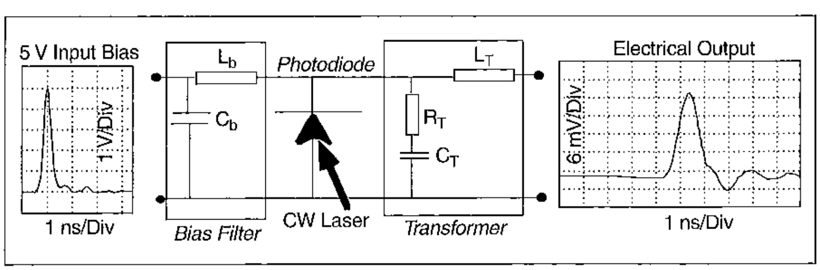
The optical waveguide grating couple is an ideal candidate for coupling out the RF modulated optical waves into photodetectors. The unique nonblocking feature of gratings allows us to have a large number of optical fanouts along the waveguide propagation, where each fanout corresponds to a TTD. Since the proposed photonic polymer-based waveguide delay lines are fabricated in a planarized geometry, while the photodetector array employed receives optical signals perpendicular to the substrate surface, surface-normal optical grating couplers are required. In order to provide effective surface-normal coupling, the microstructure of the 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 a tilted-surface relief microstructure [9,10].

The tilted waveguide grating coupler is fabricated by using a reactive ion etching (RIE) technique. In this process, the optical channel waveguide is first fabricated using photolithography. The fabricated channel waveguide has a thickness of 10 µm and a width of 50 µm. For simplicity, glass substrate is selected, which serves as the waveguide bottom-cladding. A thin aluminum metal mask is also needed on top of the channel waveguide. Then a 500 Å aluminum layer is coated on top of the waveguide by using electron beam evaporation, followed by a layer of 5206E photoresist with a spin speed of 3000 rpm. The grating pattern on the photoresist was patterned by a photo mask, which was then transferred to the aluminum layer by wet etching, to open grating-like windows on top of the waveguide. We used an RIE process with a low oxygen pressure of 10 millitorr to transfer the grating pattern on the aluminum layer to the polyimide layer. A Faraday cage [12] was used. To form the tilted grating pattern on the polyimide waveguide, the sample inside the cage was placed at a tilted angle of 40° with respect to the incoming oxygen ions. The final step was to remove the aluminum mask by another RIE process. The waveguide tilted grating couplers were successfully fabricated, and Fig. 4 shows the scanning-electron-microscope picture of the fabricated piece.

The gratings are designed to surface-normally couple the laser beam out of the waveguide at an operating wavelength at 1060 nm. A large number of gratings can be fabricated on top of the waveguide simultaneously. The output coupling efficiency is measured at 5% when a YAG laser with an output wavelength of 1060 nm is employed. Coupling efficiency can be well controlled by adjusting the grating depth from 1% up to 8%. The nonblocking nature of the waveguide grating allows a large number of fanout along the waveguide propagation. In other words, a large number of optical TTDs can be generated along the waveguide propagation with the delay time equal to the time of light flight along the waveguide circuit.

Detector-Switched Optical True-Time-Delay Lines

Figure 5(a) shows the photo of a polymeric waveguide TTD line fabricated on a 8 cm long glass substrate with waveguide thick-



6. Electrical diagram for measuring the switching speed of biased detectors.

ness of 10 μm and width of 50 μm. Surface-normal waveguide grating couplers are fabricated with a 50 μm coupling length and 10 mm separation. The surface-normal optical outputs are coupled into a high-speed two-photodetector array, placed right under the waveguide delay line. The electrical output of two high-speed photodetectors are electrically combined with a single output. The bandwidth of these detectors is ~60 GHz with 5 V bias voltage. The output of the electrical response from the detectors is first amplified through a 20 GHz microwave amplifier and then connected to a sampling scope for measuring the optical true-delay times.

Figure 5 shows the schematic diagram for measuring the optical true-time-delays. In the experiment, the delay-time interval of the optical waveguide TTD line is measured by employing a Ti:Sapphire femtosecond laser system. A sequential equivalent time sampling technique is employed for measuring the small time delay (~50 ps). Since the delay signal is repetitive, samples may be acquired over many repetitions of the signal, with one sample taken on each repetition. When a synchronous trigger is detected, a sample is taken after a very short but well-defined delay. When the next trigger occurs, a small time increment is added to this delay and the scope takes another sample. This process is repeated many times until the time window is filled. This allows the oscilloscope to accurately capture signals whose frequency components are much higher than the scope's sample rate. A 50 ps delay interval, corresponding to a 10 mm fanout separation of the polymeric waveguide delay line, is obtained using this setup, and the result is also illustrated in Fig. 5(b). The uncertainty due to jittering is estimated to be less than 5 ps for this experiment.

The detector-bias-switching is successfully obtained by launching a short electrical pulse into a high-speed MSM photodetector bias circuit while monitoring the photodetector output response under a CW optical RF illumination. Figure 6 shows the electrical diagram of the experiment. A 500 ps electrical pulse is coupled into the detector bias circuit. A high-speed electro-optic response is obtained at the photodetector output end. The output pulse is measured with a linewidth of 1 ns, which implies a nanosecond switching speed for the photodetector-switched optical polymeric waveguide TTD line.

Conclusion

Using photonic phased-array antennas in conjunction with orbiting satellites is an ideal method to bring high-bandwidth information to any aircraft in any location. Polymeric waveguide technology, including ultra-low-loss polymeric waveguides, efficient waveguide grating couplers, and optical waveguide amplifiers, offers a unique hybrid integration in realizing advanced photonic phased-array antennas based on optical TTDs. Such a hybrid integration of 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 reduces not only the cost associated with optoelectronic packaging but also the system payload, with improved reliability for airborne applications. The integrated detector-switched optical polymeric waveguide TTD line is one very promising result in this field.

Acknowledgments

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