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Polymer-based Photonic Phased-array Antenna System based on Detector-switched optical Blass Matrix True-time Delay Steering

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Sponsors: AFOSR and BMDO.

Optical Interconnects Group ***The University of Texas at Austin***

In this paper, we will report our progress on the substrate-guided wave optical true-time delay technique for photonic phase-array antenna. We will present our new optical TTD module design, and the work for PAA system demo.

Advantages of Proposed Photonic PAA

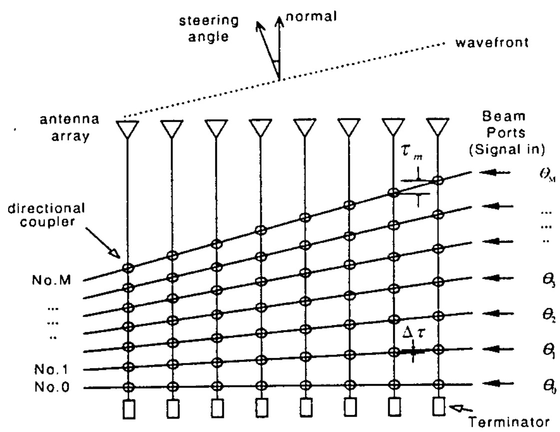
- Ultra-wide instantaneous radiation bandwidth without beam squint.
- Easily work at high RF frequency (18-26.5GHz in demo).
- Compact and low weight.
- Reliable and avoid EMP attack.
- Remote control.
- Wavelength tuning ability to provide fine-tuning of beam steering angles.
- Easily reconfigured and high steering speed.

Like other photonic PAA technique, our structure can provide ultra-wide instantaneous bandwidth for PAA, without beam squint, which means when you change microwave frequency, the steering angle will not change.

In addition, the optical beamforming network will have very high package density (2.5 delay lines/cm^2) and low weight. It will be more reliable and be able to avoid the electromagnetic pulse attack. Can easily work at high RF frequency, especially at millimeter wave, which is very difficult for electrical method, because no practical microwave transmission line exists.

Photonic PAA can let us put all the signal processing unit in some control center, and transfer the signal to remote antenna head through fiber optic link.

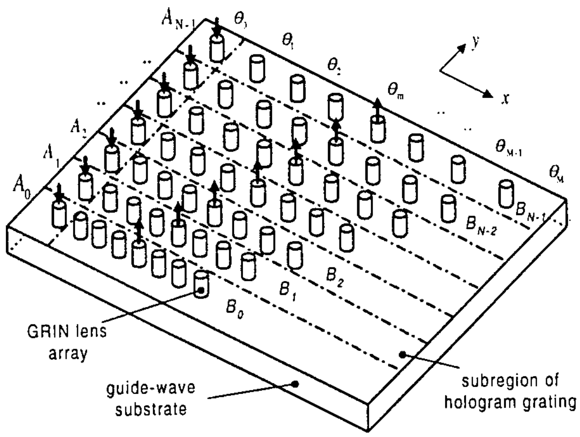
Beamforming Matrix of PAA



Blass matrix for multi-beam forming or steering.

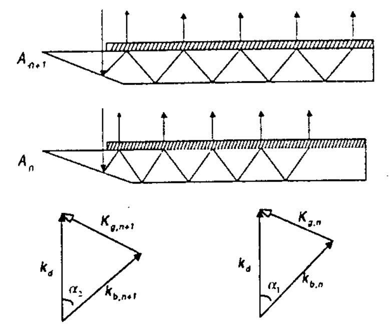
The beam steering in PAA can be accomplished by this beamforming matrix, or called Blass matrix. When you send signal into the different line, you will get different steering angle. Each node is the direction coupler to cross-connect the transmission lines. Our new photonic TTD module will realized this matrix in optical domain.

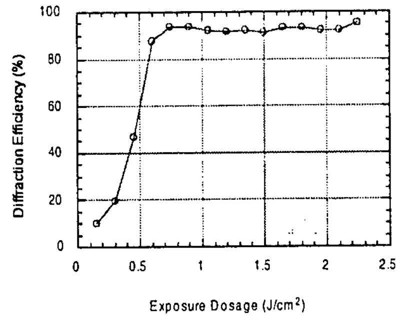
Polymer-based Substrate-guided Wave optical True-time Delay Module



The idea of optical Blass matrix based on substrate-guided wave fanout structure is making a series of bouncing paths within the guiding-wave substrate with different step-lengths that actually become an increasing sequence. Then, we bring $\Delta\tau$ to the neighboring antenna elements by the difference between the time-step of the neighboring bouncing path and the accumulation of this difference. The resulting optical true-time delay module will have the structure as shown in the slide.

Design of the hologram grating on guide-wave substrate



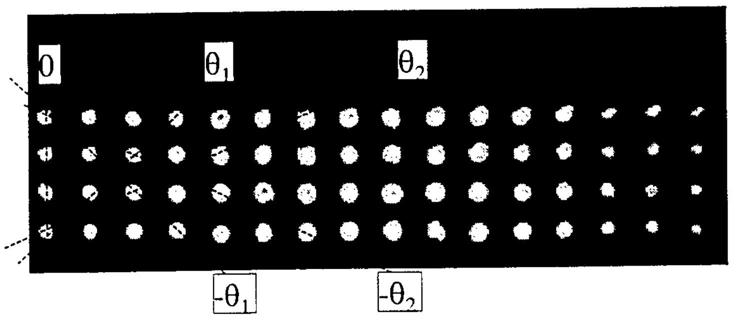


Delay introduced at No. m fanout:

$$k_{b,n+1} + K_{g,n+1} = -k_d \qquad k_{b,n} + K_{g,n} = -k_d \qquad \tau_m = m \cdot \Delta\tau = m \cdot \frac{2nh}{c}\left[\frac{1}{\cos(\alpha_{n+1})} - \frac{1}{\cos(\alpha_n)}\right]$$

The module is built on the guiding-wave substrate with a thickness of h. On the top-surface of the substrate, there is a transparent grating film made by the hologram recording. The whole grating surface was divided into several sub-regions, numbered by n. The input grating can be replaced by wedge mirror. As shown, each sub-region of grating has the different diffraction angle α_n The desired $\{\alpha_n\}$ sequence should be able to let the introduced time delay between fanout (n, m) and (n+1, m) become m times of $\Delta\tau$, so time delay for m-th steering angle can be obtained as shown in the formula.

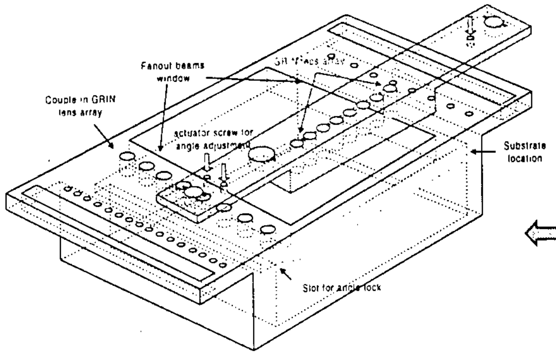
Polymer-based 2-Dimensional Waveguide fanout for Uniform Blass Matrix



Delay step: 50 ps

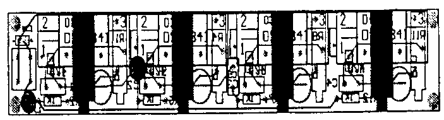
Fanout beam array of the uniform Blass matrix we have made. The diffraction angles is uniform so the $\Delta\tau$ is realized by selecting different bouncing step number from each bouncing path.

TTD Module Package Design and PIN Array PCB

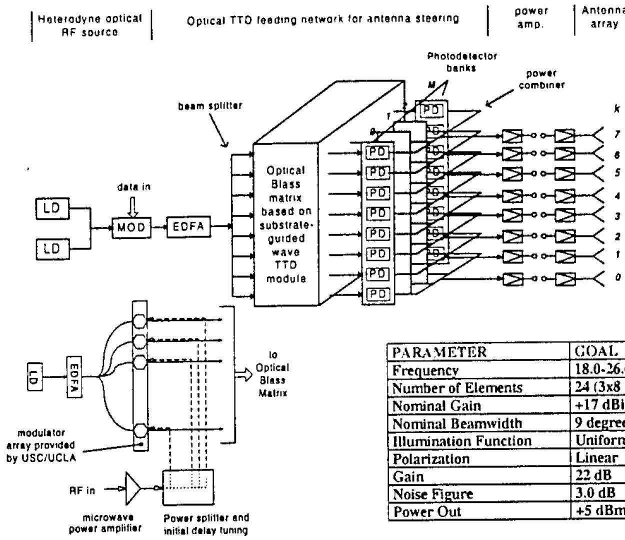


The objective of this package design is to couple the 8×8 asymmetric fanout beam array into fibers, through a corresponding GRIN lens array.

The PCB layout (half) of the PIN photodetector bank (linear array), which will be used to convert the optical signals from one column of the fanout array.



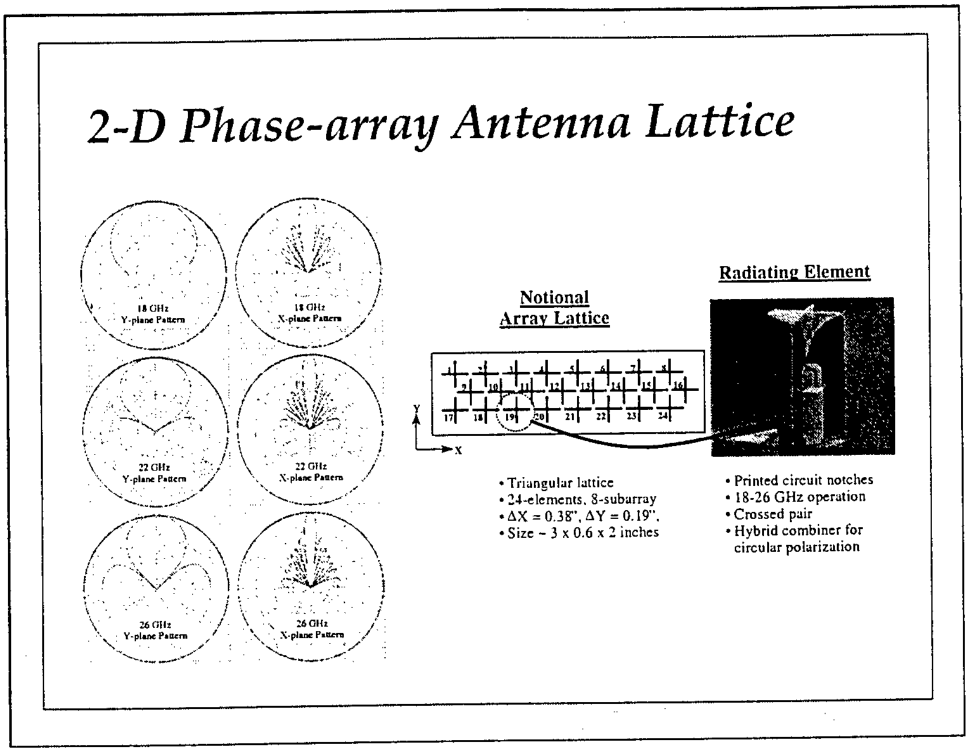
System Configuration



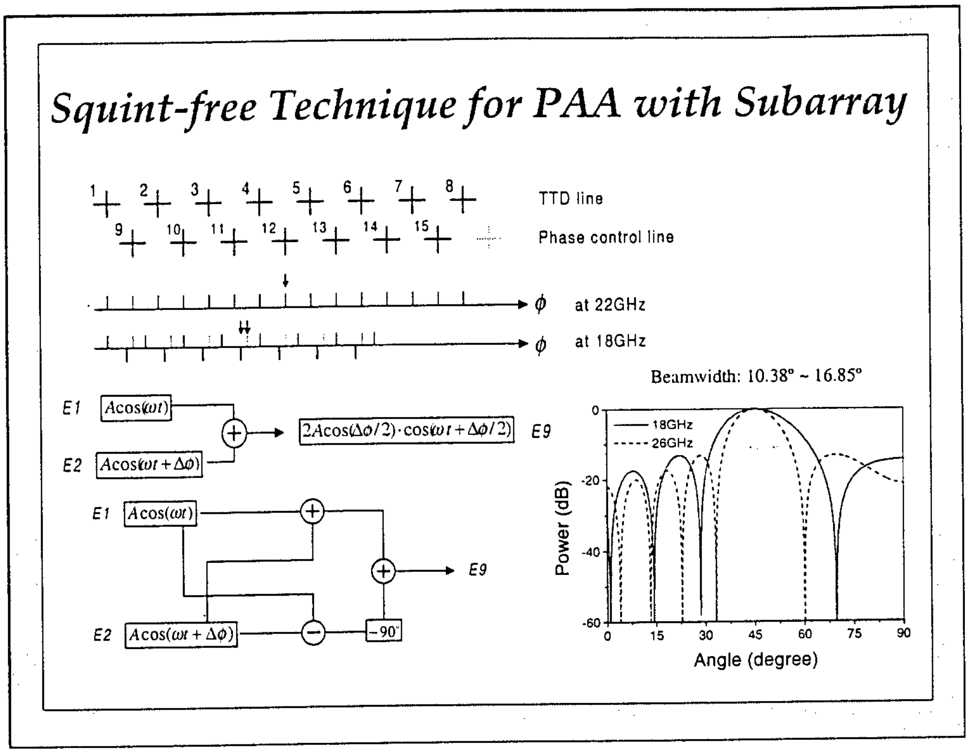
Elements's number $K = 8$
Steering resolution 3-bit
Scanning range: 0 ~ +/-45°

PARAMETER	GOAL
Frequency	18.0-26.0 GHz
Number of Elements	24 (3x8 array)
Nominal Gain	+17 dBi
Nominal Beamwidth	9 degrees x 52 degrees (fan beam)
Illumination Function	Uniform (-13dB nominal sidelobes)
Polarization	Linear
Gain	22 dB
Noise Figure	3.0 dB
Power Out	+5 dBm

System demonstration will be proceeded with heterodyne RF source first, then use USC/UCLA high speed modulator array to do the full demonstration.

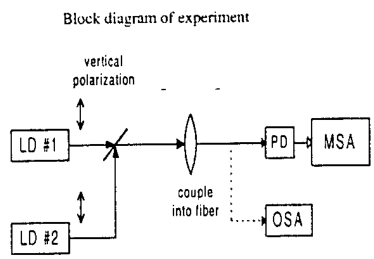


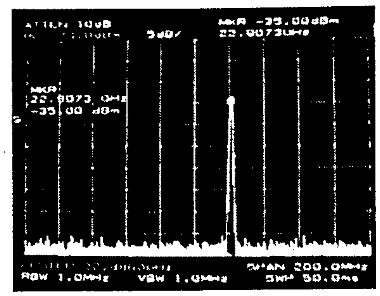
The radiation pattern (directivity) of the 2-D PAA system. The array lattice structure and the element of the antenna are shown here, which can provide the wideband beam steering without grating lobe in as high as 18GHz-26GHz frequency range.



By this squint free control technique for subarray, we will be able to use only 8-channels of TTD signal to control 2-D PAA array with 2×8 or even 3×8 elements. The principle is to use the a special operation between the neighbored TTD signals to produce the control signal for the elements within the subarray. So, we can reduce half the number of the steering control variables.

Heterodyne Photonic RF Source





- Power coupled into fiber: -4 dBm/ch
- RF frequency: ~ 30 GHz
- RF signal power: -35 dBm

Theoretical limit of conversion efficiency:

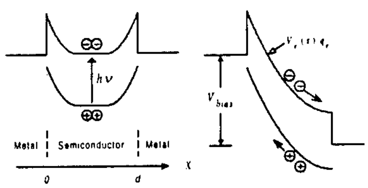
$$P_{RF} = \frac{1}{8} Z_L R^2 (P_{opt.p})^2$$

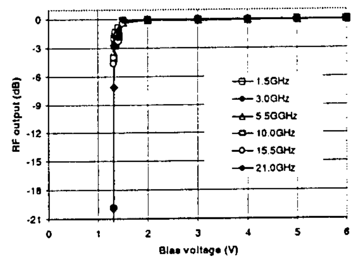
Or, in dBm: $P_{RF} = 20 \cdot \log(P_{opt.p}) - 36.9$
$= -32.9\,\text{dBm}$

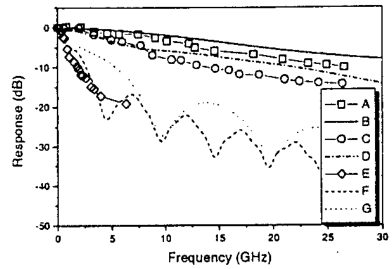
The heterodyne photonic RF source has been successfully demonstrated, with the conversion efficiency approaching the theoretical limit, as shown above. The signal amplitude is stable, the spectrum is clear. The RF spectrum width is determined by the linewidth of the lasers. As we observed, less than 1MHz spectrum width is obtained. The RF frequency can be tunable up to 32 GHz limited by the responding speed of the photodetector.

Switching Operation of Wide-band Photodetectors

Switching characteristic of MSM.

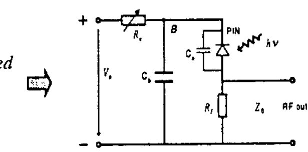






Switching of PIN: V_{J0}=1.9V (A&B), 0.5V(C&D), 0.05V(E&F), 0.1V(G). A, C, E are experiment data. B, D, F, G are theoretical curve.

V_{J0} is adjusted by this circuit



(1) The Metal-Schottcky-Metal (MSM) photodiode has a potential well in its junction band structure. It will prevent photocurrent when the bias voltage is less than threshold value. The test result of switching property is quite close to the theoretical calculation.

(2) The drift velocity of the photo-carriers depends on the electrical field intensity in junction. So, through control the junction voltage, the PIN photodetector can also be used as an optoelectronic switch for photonic RF signal. The up-right curves is the test result and theoretical calculation. The down-right figure is the operation circuit.

Conclusion:

- *Novel detector-switched optical Blass matrix for phase-array antenna true-time delay steering have been proposed and designed.*
- *The photonic phase-array antenna system based on above optical TTD module has been designed and under preparing.*
- *A new squint free technique for photonic phase-array antenna based on sub-array structure is proposed. Simulated result of the far-field radiation pattern has been presented.*
- *The heterodyne system for photonic RF signal generation has been built, which conversion efficiency approaches to theoretical limit.*
- *The switching mechanism of wide-band MSM and PIN photodetector has been studied.*
- *The whole system will work on 18-26GHz, which will be of the photonic PAA demonstration with the highest RF frequency.*