A Coherent Optically Controlled Phased Array Antenna System

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Abstract—**A true-time delay, optically controlled phased array antenna system whereby a large number (100–2500) of antenna elements can receive a series of microwave delays via use of a coherent optical carrier signal is described. Both transmit and receive antenna arrays are described, and the signal-to-noise ratio for a 128 channel system is calculated to be ~40 dB with an optical link loss of only ~3 dB for a 1 GHz instantaneous bandwidth at a wavelength of $\lambda = 1.55$ μm. It is shown that the use of coherent optically controlled phased array antennas provide improved controllability and immunity from noise and system losses over other architectures currently being investigated.**

I. Introduction

Optically controlled phased antenna arrays are currently hampered by the extreme complexity required in efficiently transmitting several hundred microwave delays from the controller to the antenna array. These difficulties are compounded by the demands of modern phased array systems including extremely high bandwidth broadcast frequencies (ranging from 20–60 GHz requiring up to 1-GHz instantaneous bandwidth per channel), stringent requirements on signal-to-noise and dynamic range, clutter cancellation, and the need for null steering and generating multiple, squint-free beams at different frequencies [1]. Most architectures distribute a series of time or phase delays to the antenna network [1], [2] via an optical switching matrix followed by amplifiers which compensate for loss (sometimes approaching 100 dB in large scale arrays). One difficulty encountered by this architecture is that all fibers which transport the microwave/optical signals from the input to antenna terminals must be of the same length so as not to introduce extraneous delays, or noise. Hence, these architectures have been proven to be limited by losses, they are difficult to implement, bulky, and costly. We describe a novel architecture based on the coherent optical transmission of signals from input to antenna array, and vice versa. The system is based on coherent, multichannel broadband transmission networks which have been investigated for applications to telecommunications. A 128-element system can have a signal-to-noise ratio (S/N) ratio as high as ~40 dB with an optical link loss of only ~3 dB at a wavelength of $\lambda = 1.55\mu$m and an instantaneous bandwidth of 1 GHz.

Fig. 1 is a schematic diagram of the transmitter. In an intensity modulated scheme, the microwave signal at frequency $\omega_\mu/2\pi$ modulates the output of the wavelength-tunable laser array to generate a signal, $A_\mu \sin\omega_\mu t$. The signal which is delayed by k time increments, Δt, is tranmitted by a laser tuned to emit at optical frequency, ω_{ok}. Hence, the signal delayed by $k\Delta t$ is given by (ignoring quadrature terms): $A_\mu \sin[\omega\mu(t + k\Delta t)]\sin\omega_{ok}t$. This signal, along with the $n-1$ other tunable delays, are then combined onto the single transmission fiber. Essentially, a "look-up" table is created that associates n optical frequencies with n delays of length $k\Delta t$. The signals are combined using couplers with optical amplifiers which compensate for combiner losses and prevent degradation of S/N. Either erbium doped fiber amplifiers (EDFA's) or semiconductor optical amplifiers (SOA's) can be used in this application. Advantages of the EDFA are a higher S/N than for SOA's, whereas SOA's offer a higher degree of device integration. Here, we examine the EDFA approach.

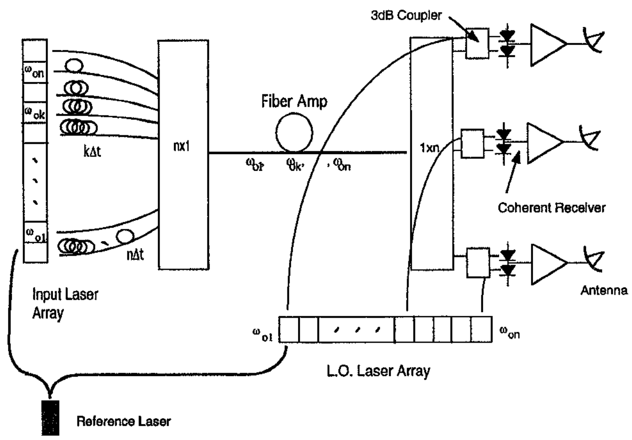

Fig. 1. Schematic diagram of a coherent phased arraytransmitter antenna.

After transmission on the fiber, the signals are distributed to the coherent receivers using an $n \times 1$ splitter. Again, optical amplifiers compensate for splitter loss and prevent undue S/N degradation. At the antenna end, each of the n optical signals are incident on n receivers, along with n LO signals that are tuned to provide receiver 1 with frequency ω_{o1}, receiver 2 with ω_{o2}, etc. Given that the kth LO is at $B_k \sin(\omega_{ok}t + \phi_k)$, then the signal at the output of the kth receiver is proportional to: $A_\mu B_k G_k \cos\phi_k \sin[\omega_\mu(t + k\Delta t)]/2$, where G_k is the product of all the gains and losses in the link. This signal is then delivered to the kth antenna at the RF frequency (typically 20-60 GHz) by frequency "upshifting" the signal. To sweep the beam, the input laser array (or, alternatively, the LO array) frequencies are changed to create

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TABLE I
DATA FOR EDFA NETWORK

Component	Optical Loss (dB)	Excess Loss (dB)*	Optical Gain (dB)	Noise Figure (dB)	Optical Signal Power Relative to Input Signal (dB)
16 × 1 Combiner Loss (L_c1)	12	0.2			−12.2
EDFA (G_a1, F_a1)			21.2	4	9
8 × 1 Combiner Loss (L_c2)	9	0.2			−0.2
Fiber Loss (L_c2)	1				−1.2
1 × 8 Combiner Loss (L_c3)	9	0.2			−0.2
EDFA (G_a3, F_a3)			10.2	4	9
1 × 16 Loss (L_c4)	12	0.2			−3.2

*Losses are taken to be 0.1 dB for each splice connection.

a new correspondence between a delay and an output antenna. Phase or freqency modulation can alternatively be employed to encode the microwave signal onto the optical carrier.

The signal is proportional to the LO strength, B_k. Typically, this can be as high as 10 mW at $\lambda = 1.55\mu$m, thus providing considerable gain at the antenna end. Both microwave amplifier and LO gain can be tuned at each antenna element to arbitrarily "shape" the beam. Frequency reference is provided to each tunable laser in the array by one of several techniques. For heterodyne detection, the receiver can tune from the IF in a frequency-locked loop [3]. Another means for providing simultaneous external reference to all n channels is to use a mode-locked laser which generates a "comb" [4] of equally spaced Fourier-component frequencies. This comb injection-locks the individual lasers which are roughly "current-tuned" to a particular frequency. Injection locking a continuously current-tunable laser using a comb of frequencies thereby changes the linear relationship between tuning current and wavelength into a "stepwise" laser output spectrum, with steps at the channel frequencies. Phase-locking using a phase-diversity receiver or a phase modulator, is needed to maintain a constant amplitude via the $\cos\phi_k$ term.

This system requires continuously frequency tunable laser arrays [5]. Using present technology, up to nearly 100 Å tuning has been demonstrated at $\lambda = 1.55\mu$m using three-section DFB lasers [6]. Given that 1 Å $=$ 12 GHz at $\lambda = 1.55\mu$m, and that each channel can occupy $a \leq 1$ GHz instantaneous bandwidth (BW), this implies $\sim$ 100 channels occupying 1.2-THz bandwidth can be accommodated. Here, the interchannel spacing must exceed the BW in analog systems by $\sim 3-5$ times to minimize interchannel and image channel interference [7]. It will be shown elsewhere that the interchannel separation is limited by the phase noise and linewidth of the semiconductor laser, given that the channel bandwidth occupied by a ~ 1 μs radar pulse is very small.

To achieve a high S/N, combiners/splitters with EDFA's are implemented as follows: The n signals are combined by m, $(n/m+1)\times 1$ passive couplers followed by m EDFA's, with n being the number of delays. The use of multiple, low gain coupler stages minimizes spontaneous emission noise common in systems which combine high loss and high gain in only a few amplifier stages. Each combiner merges n/m signals along with a pump signal for an EDFA [8]. After amplification, the signals are combined by an m$\times$ 1 passive coupler and transmitted along the fiber transmission line. An EDFA is also used on the transmission line to further improve signal level. Similar to the combiner, the signals are split by a $1\times(m+1)$ passive splitter, amplified by m EDFA's, and then further split by m $1\times(n/m)$ passive splitters.

The system signal-to-noise ratio, $(S/N)_s$, and loss budget are calculated assuming that the signals are transmitted at a channel frequency of 1.55 μm with BW = 1 GHz, and with 5km between terminals. $(S/N)_s$ is given by $(1/F)(S/N)_{trans}$, where the laser transmitter RIN at 1 GHz is $(S/N)_{trans}$ =$\sim$70 dB [9] and F, the noise figure, is found using [10]:

$$F = L_{c1}F_{a1} + \{L_{c1}/Ga1\}\{L_{c2}F_{a2}-1\} + \cdots + \{L_{c1}L_{c2}\cdots L_{cM-1}/G_{a1}G_{a2}\cdots G_{aM-1}\} \times \{L_{cM}F_{aM}-1\}.$$

Here, L_{ci} is the loss of the ith stage, F_{ai} is the noise figure of the i-th amplifier, and G_{ai} is the gain of the ith channel. Table I gives performance data for the main components of the system for a 128-channel link with $n = 128$ and $m = 8$. The optical gain and output power for an EDFA can be as large as $\sim$ 22 dB and 18.5 dBm, respectively, and the noise figure is 4 dB [11]. The overall noise figure of the EDFA implementation is $\sim$ 30 dB and the $(S/N)_s$ = 70dB $-$30dB $=\sim$40 dB. From laser transmitter to the optical receiver, the system has $\sim$ 3 dB of optical loss. Additionally, the gain of the EDFA is relatively flat between 1.530μm and 1.560μm [11]. Therefore, the $(S/N)_s$ performance for all channels of a WDM system is expected to be $\sim$ 40 dB.

The spectral bandwidth of an EDFA is $>$ 0.1 μm. Thus, to further extend the number of channels in a multiple beam or large array system, a wavelength multiplexed approach such as that depicted in Fig. 2 is employed. Each 100-Å subarray is combined onto the single carrier fiber using gratings or filters. Given BW = 1 GHz, and a *very conservative* channel separation of 5$\times$ BW to eliminate undue interchannel interference in a heterodyne system where $\omega_{I.F.}/2\pi$ = BW, this 12-THz system has a very large channel capacity of 2500 channels [2]. Finally, in Fig. 3, we show a schematic of the receiver antenna. Comparing this with Fig. 1, similar components and techniques are used for both transmit and receive.

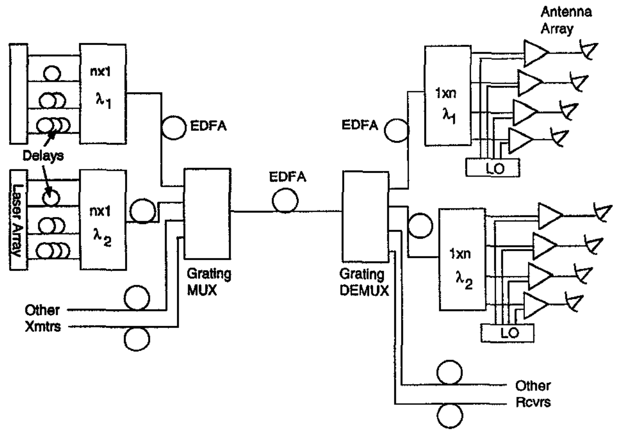

Fig. 2. Wavelength multiplexed, very broad-band phased array antenna.

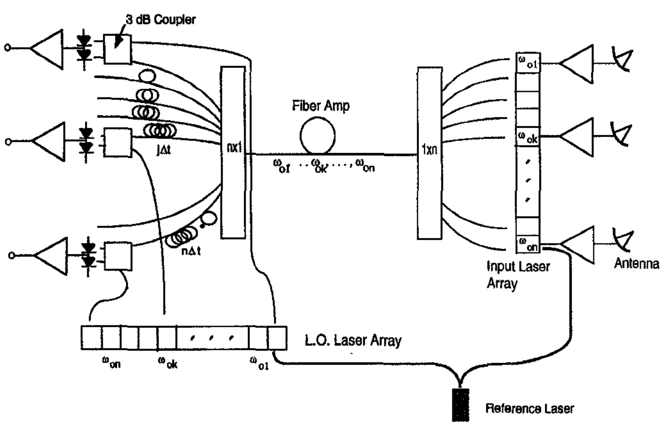

Fig. 3. Schematic diagram of a coherent phased array receiver antenna.

In summary, the coherent optically controlled phased array: 1) accommodates $\sim$ 100 channels in a single fiber. With the addition of a multi-wavelength system, over 2500 channels can be accommodated in this single fiber architecture. 2) Can be used for null steering, multiple beam formation, and squint-free multiple frequency operation. This flexibility results from the high gain due to a combination optical and electronic amplification, and LO gain, and the rapid tunability of the gain elements. The slowest tunable element is the LO, where restabilization of frequency must occur on a time scale somewhat shorter than the beam scan time ($\sim$ milliseconds). 3) Employs components and techniques already developed for multichannel coherent communications, taking advantage of progress in tunable lasers, optical amplifiers, and coherent phase and polarization diversity receivers. However, practical realizations would need to incorporate a high degree of integration of both lasers and receivers. Potentially, a 128 element array can deliver very high power signals to the antenna with $\sim$ 3 dB of optical loss and an S/N of $\sim$ 40 dB for BW = 1 GHz at $\lambda = 1.55\ \mu$m.

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