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System Architecture of MMIC-Based Large Aperture Arrays for Space Applications

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SYSTEM ARCHITECTURE OF MMIC-BASED LARGE APERTURE ARRAYS FOR SPACE APPLICATIONS

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Abstract

The persistent trend to use millimeter-wave frequencies for satellite communications presents the challenge to design large-aperture phased arrays for space applications. These arrays, which comprise 100-10,000 elements, are now possible due to the advent of lightwave technology and the availability of monolithic microwave integrated circuits. In this paper, system aspects of optically-controlled array design are studied. In particular, two architectures for a 40 GHz array are outlined, and the main system-related issues are examined : power budget, synchronization in frequency and phase, and stochastic effects.

Introduction

The field of satellite communications has seen a major expansion in the last two decades. As demand for high-capacity radio links grows, utilization of higher frequency bands is expected to increase, with communication satellites operating in millimeter wave and optical frequencies. In the 1984 list of satellite locations[1] there already existed more than 15 systems operating at frequencies above 20 GHz.

The progression into higher frequencies is tied to advances in microwave and optical technology. The advent of the monolithic microwave integrated circuit (MMIC[2,3]) and the optical fiber has provided the designer of satellite communication systems with new means to transmit, receive and process wide-band communication signals. It now allows the design of antenna arrays for satellites, which hold the promise of producing an electronically steerable pencil beam as an alternative to presently-used parabolic dishes.

The large aperture arrays, needed for millimeter-wave satellite applications, require 100-10,000 antenna elements, and therefore present a real design challenge involving distribution and phasing of RF signals to the antennae. Spacing the elements at $\lambda/2$ distance apart from one another means that a 10,000 element planar array will occupy only about $1\,m^2$ of area, resulting in formidable challenges in the areas of heat dissipation, wire routing and electromagnetic interference. Moreover, proper synchronization in frequency and phase of the independent radiating elements, which is required to shape and steer the beam, becomes a difficult task at frequencies above 20 GHz.

A possible solution to the problems posed by the need for an elaborate signal distribution network is employment of fiber-optic technology. Fibers are known to have the following merits:

- small size (less bulky cable network)
- light weight (about one order of magnitude lighter than conventinal microwave coaxial waveguides)
- immunity to EMI, RFI, and EMP
- virtually no crosstalk
- large bandwidth capacity
- high cable flexibility
- low attenuation over a large bandwidth

Utilization of these advantages relies on the ability to demonstrate that a fiber-optic-based network is capable of distributing a source signal to the array elements within the required tolerances for phase and frequency accuracy. These capabilities have been demonstrated in laboratory experiments, using indirect optical injection locking of millimeter wave sources[4,5], and piezoelectric-crystal-based phase shifters[5]. They constitute the basis upon which large-aperture optically-controlled arrays can be envisioned.

In this paper, we outline possible architectures linking the microwave rear-end and front-end of a millimeter wave array through an optical distribution network. We present the major issues involved with system design and some of the tradeoffs which a hybrid microwave/optical system presents.

Basic array structure

The generic architecture of the phased array is described in figure 1. We recognize 4 main subsystems:

- The central processing unit which controls the beamforming process, as well as the connections with auxilliary processing devices for communications (signal generation and signal processing)
- Master oscillator, generating the primary microwave reference signals
- The feed-distribution and phasing (implementing beam shaping and signal transfer to the array)
- The planar array, organized in a rectangular shape

This basic architecture requires three types of signals:

- Carrier: the millimeter wave main signal
- External communications: emanating at external devices, modulated on the carrier, having a bandwidth of approximately 1 GHz
- Internal communications: emanating at the CPU for control of the other subsystems, having bandwidth of order of few tens of MHz

The main criteria by which the array is assessed are:

- Beam shape (directivity, beamwidth)
- Steering (step response, dynamic behavior)
- Span
- Resolution
- Power requirements (DC, microwaves)
- Immunity to interference
- Reliability and Maintainability

Although our studies are general in nature, it is instructive to focus our presentation on a specific system. The array that we shall refer to in this paper has the following basic specifications:

- Frequency: 40 GHz
- Transmitted power: ~ 100 Watts
- Mechanical configuration: rectangular $2^5 \times 2^6$ elements
- Spacing between elements: $\lambda/2$
- Minimum span: a cone with angle 30°.

Integration of optical technology in the array

We have mentioned the main features of optical fibers, which make their use an attractive alternative for cable distribution systems. These features have caused the proliferation of optical systems for digital communications. The applications which the MM wave array calls for are, however, mainly analog. The required tasks to be implemented in the optical domain are:

- Reference signal distribution (with prescribed requirements for frequency and phase synchronization)
- Modulation and demodulation of a 1 GHz wide signal on an optical carrier (for communications or data)
- Phase shifting with prescribed dynamic range and dynamic behavior (for beam forming)

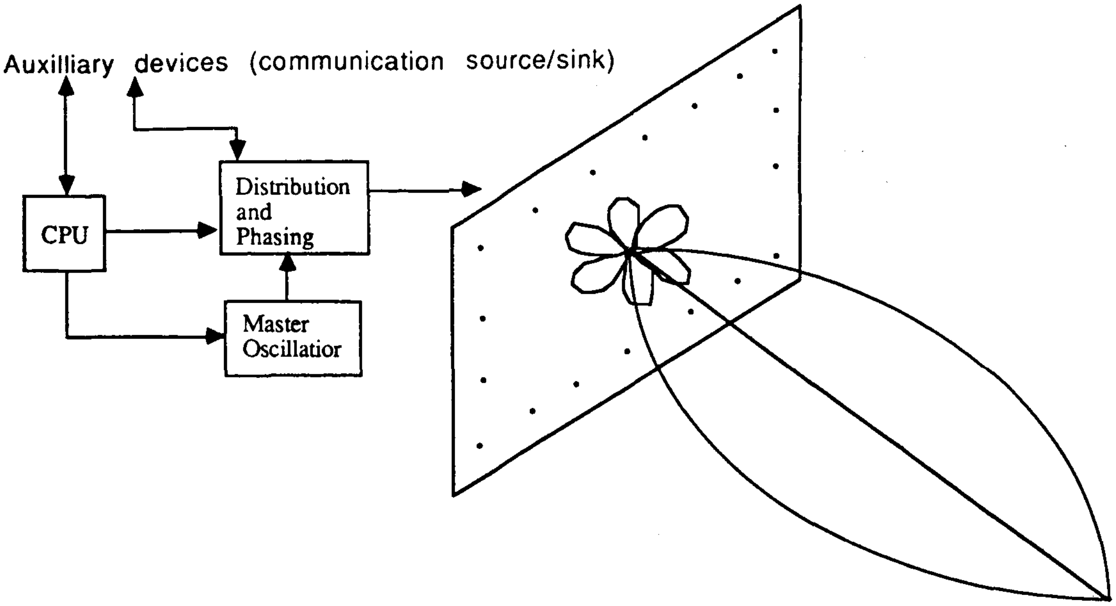


Figure 1: Basic array architecture

There are several alternatives regarding the degree of integration of optics into the array. The simplest is to use optics only for internal communications within the arrray - for control purposes. Then a hybrid optical/ microwave system can be envisioned. For this case the milllimeter wave reference signal, as well as the control signal distribution, is implemented in the optical domain, while phase shifting is performed in the microwave domain[3]. A still higher degree of integration will perform phase shifting also in the optical domain.

In this paper, two architectures are considered, depicted in figures 2 and 3. Both architectures use an identical hybrid microwave/optical reference distribution scheme, which uses microwave devices for signal amplification, and optical devices for RF signal division and transmission. The two configurations differ in the manner that phase shifting is carried out. Architecture 1 (figure 2) performs all phase shifting in the transmit/receive module (using a conventional microwave phase shifter). Architecture 2 (figure 3) distributes phase shifting along the reference signal path, and performs the shifting optically (using novel digital and analog optical phase shifters).

The role of synchronization. Synchronization plays a key role in the successful operation of a phased array. The impact of phase and frequency inaccuracies on overall array performance has been the subject of numerous investigations (see for example reference 6 and its references). It has been shown the phase inaccuracies degrade signal to noise ratio[6], change the beam pattern, including directivity and sidelobe level[7,8] and introduce beam pointing errors. Frequency synchronization is also a requirement for coherent communications, and synchronization errors cause degradation in parameters such as post-detection signal-to-noise ratio and probability-of-error versus carrier-to-noise ratio in digital communications[9]. These effects are of major importance for spread spectrum applications of a millimeter wave array, rendered possible by the high frequency of the carrier, which allows realization of large processing gains[10]. The problem of frequency synchronization is even more extenuating in antenna systems utilizing MMIC T/R modules because ot the large number and independence of these elements.

Recently, several technological advances in the area of synchronization have been reported in conjuction with optically controlled arrays. Among these are:

- Indirect optical injection-locking of multiple X-Band oscillators[4]
- Indirect optical injection locking of an IMPATT oscillator at 39 GHz[5]
- A true time-delay phase shift - induced in the optical domain[5]

These developments are expected to allow employment of optical fibers as carriers of frequency synchronization signals, and providers of continuous phase shift. The basic synchronization system (Figure 4) involves a master oscillator, a laser, a pizoelectric phase shifter, a PIN detector and an IMPATT oscillator. The laser diode is operated in the nonlinear region, creating high-order harmonics, one of which is used to lock the slave oscillator. The resulting (40 GHz) signal can then be AM modulated, through a mixer, by the communications signal transmitted via another FO link[5].

The piezoelectric ring is biased by high voltage DC, creating expansion of the ring and stretching the fiber that is wrapped around it. The resulting phase shift, at a particular frequency, is determined by the field-induced strain in the piezoelectric device and by its geometry

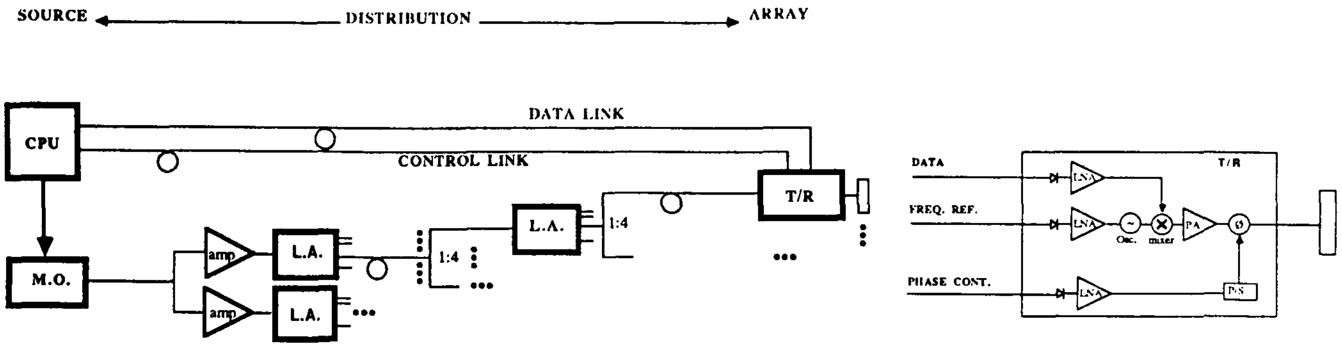
$$\Delta\Phi = 2\pi\,(\Delta l / \lambda_g) = 2\pi^2\,ND \times 10^{-5} V / \lambda g \qquad (1)$$

where

$\Delta\Phi$	phase shift in radians
Δl	stretching of the fiber length (m)
λ_g	wavelength of the RF reference signal(m)
N	number of turns
D	diameter of piezoelectric ring (m)
V	supply voltage (KV)

The architectures depicted in figures 2 and 3 make use of a semiconductor laser array (that combines eight high-speed lasers, all driven by the same RF circuit on a single chip). The first stage consists of two such arrays, each driving eight 1:4 splitters. The second stage has 64 arrays, each driving a 4 element sub-array. Synchronization is performed at each T/R module, using a detector-amplifier-oscillator chain like the one described in figure 4.

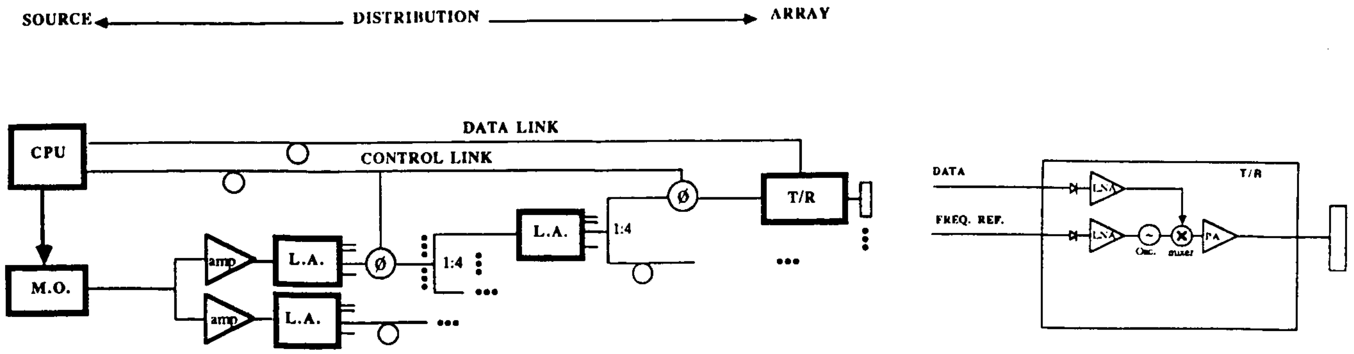
Phase shifting in architecture 1 is performed at the T/R modules. The control signals are distributed via FO links to the T/R modules where they are detected and utilized to drive conventional microwave phase shifters. Phase shifting in architecture 2 is facilitated in two stages: following the first layer of laser array chips, 64 discrete optical phase shifters are used, each corresponding to 32 antenna elements. The progressive phase shift between elements is provided by 512 piezo-electric rings; each ring provides phase shift for four antenna elements.



2 b. T/R Module

2 a. System Configuration

Figure 2. Architecture 1



3 a. System Configuration

3 b. T/R Module

Figure 3. Architecture 2

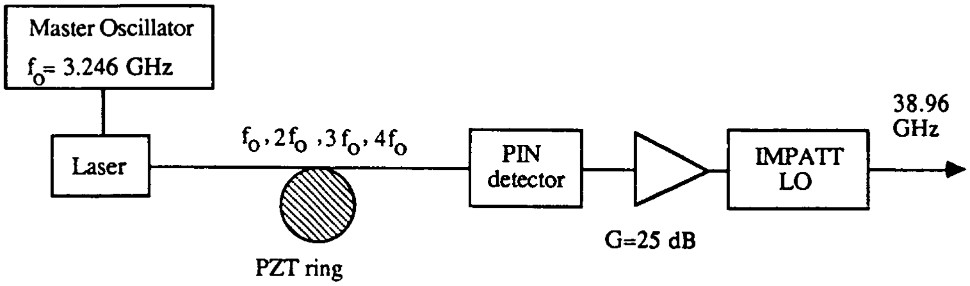


Figure 4: Frequency synchronization and phase shifting in the optical domain[4]

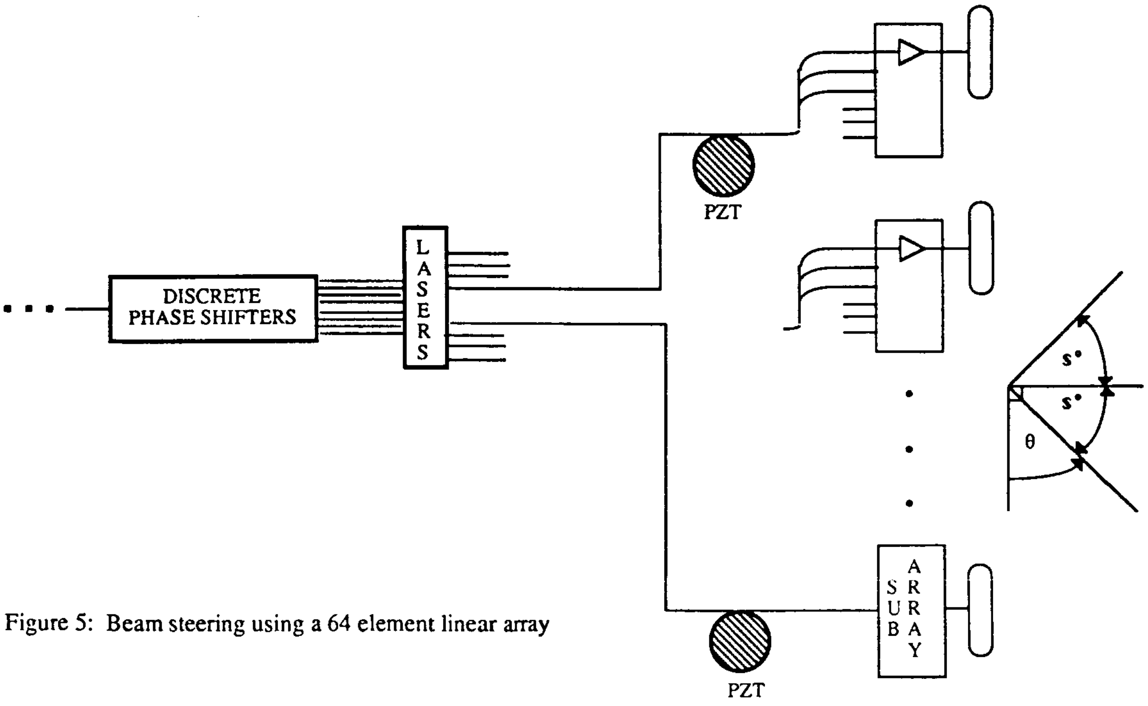


Figure 5: Beam steering using a 64 element linear array

Component list and power requierments. Table 1 summarizes the types and numbers of elements needed for each configuration and gives an estimate of the DC power requirements that are involved. The numbers quoted in the table represent measured values for discrete, commercially-available components. The power consumption can therefore be reduced substantially through integrated design. For example, most of the 7 Watts consumed by the 20 dB low-noise amplifier is for biasing and voltage regulation. If these functions are implemented centrally for all amplifiers, the consumption of each amplifier can be reduced to less than 0.1W.

About one-third of the required power is related to the loss in the distribution network due to microwave-to-optical and optical-to-microwave conversions. These losses are to be compensated by additional amplification (the low-attenuation advantages of the optical fiber are not significant due to the short length of cables in this application). The difference between the configurations in terms of power requirements is small, as the phase shifters are not major contributors to the overall consumption.

Table 1a. Power Budget for Architecture 1

Type of component	Location	Number	Power/unit	Power	Heat Diss.
Preamplifier	Distribution (level 1)	2	1 W	2 W	
Laser Array	Distribution (level 1)	2	2 W	4 W	
Laser Array	Distribution (level 2)	64	2 W	128 W	100 W
Photo Detector for Freq. Synch.	T/R module	2048	~0	~0	~0
LNA for Freq. Synchronization	T/R module	2048	7 W	14.5 kW	10.8 kW
Local Oscillators	T/R module	2048	0.8 W	1.6 kW	1.2 kW
Mixer	T/R module	2048	~0	~0	~0
Photo detector for Phase Control	T/R module	2048	~0	~0	~0
LNA for Phase Control	T/R module	2048	1 W	2 kW	1.3 kW
Digital Circuitry for Phase Control	T/R module	2048	~0	~0	~0
Microwave Phase Shifters	T/R module	2048	0.46 W	1 kW	0.4 kW
Photo Detector for Data	T/R module	2048	~0	~0	~0
LNA for Data	T/R module	2048	1 W	2 kW	1.3 kW
Power Amplifiers (2 cascaded)	T/R module	2048	9 W	18.5 kW	13.8 kW

Table 1b. Power Budget for Architecture 2

Type of component	Location	Number	Power/unit	Power	Heat Diss.
Preamplifier	Distribution (level 1)	2	1 W	2 W	
Laser Array	Distribution (level 1)	2	2 W	4 W	
Digital Optical Phase Shifters	Distribution (level 1)	64	4 W	256 W	170 W
Laser Array	Distribution (level 2)	64	2 W	128 W	100 W
Analog Optical Phase Shifters (PZT)	Distribution (level 2)	512	0.05 W	25 W	
Photo Detector for Freq. Synch.	T/R module	2048	~0	~0	~0
LNA for Freq. Synchronization	T/R module	2048	7 W	14.5 kW	10.8 kW
Local Oscillators	T/R module	2048	0.8 W	1.6 kW	1.2 kW
Mixer	T/R module	2048	~0	~0	~0
Photo Detector for Data	T/R module	2048	~0	~0	~0
LNA for Data	T/R module	2048	1 W	2 kW	1.3 kW
Power Amplifiers (2 cascaded)	T/R module	2048	9 W	18.5 kW	13.8 kW

The two generic architectures suggest a host of variations:

- Balance microwave/optics : we clearly have a tradeoff, with the possibility of substituting components from one domain by functional equivalent units from the other. One may ask for the (optimal) balance between operations in the microwave and optical domains, with respect to a specified performance index; this index includes parameters like cost, power consumption and heat distribution.

- Degree of centralization in control : both configurations assume a centralized "smart" controller, providing each shifter -- or layer of shifters -- with a phase lag command. This approach can be changed to a decentralized one: the main CPU provides local processors with desired-phase information. The local processors in turn tune the shifter under their control. These different approaches should be assessed mainly versus wiring requirements, with the former approach requiring more extensive wiring than the latter.

- Degree of centralization in phase : the distribution of phase shift in the various stages of the array presents another tradeoff. Here we can have a single phase shifter per antenna, or a host of shifters located at each layer. At issue here are primarily considerations of mechanical structure and heat distribution. A-single-phase-shifter-per-antenna approach will require a large phase difference bewtween the 1st shifter and, say, the 2^6th, while a "mixture" of shifters, distributed over the layers, will impose more command and control routes, as well as possible limitations on span and resolution.

Issues in beam control

Allocation of phase shift in the array. To illustrate the system issues associated with array design we consider the problem of phase allocation in the array of architecture 2. We assume that two types of phase shifters are available:

Phase shifter 1	Analog, based on piezoelectric ring Minimum phase shift -zero Maximum phase shift - ϕ_{Mp}
Phase Shifter 2	Digital, based on optical delay in fiber Minimum phase shift - ϕ_{md} Maximum phase shift - unlimited

Our task is to provide a span of ±S° around broadside direction with minimum resolution ΔS. We shall consider a 2^6 - element linear array, which is part of the $2^5 x 2^6$ planar array (figure 5).

The progressive phase shift, when the beam is pointed to direction θ, is calculated from the relation

$$\alpha = - \beta d \cos\theta = - \pi \cos\theta \tag{2}$$

which in our case gives

$$\alpha: -\pi \sin s \text{ — } \pi \sin s \tag{3}$$

For a typical $S=\pi/6$ we get that α is between $-\pi/2$ and $\pi/2$, with the total phase shift from first to last element up to 32π. Clearly, realization with a single phase shifter per antenna is not the way to go.

Let the total phase shift from first to last element be ϕ_T. The discrete phase shifter is capable of phasing each 8-element subarray with phase $n(\phi_T / 8)$; n=0, .., 7,and the analog phase shifter covers the gap between every two subarrays, by introducing a progressive phase shift of $\phi_T/64$ between elements. We therefore get a minimum change in the progressive phase shift (corresponding to $\phi_T/8 = \phi_m$) of $\phi_{md/8}$. The minimum attainable resolution over the span $\pi/2-S$ to $\pi/2+S$ is

$$\max_{\alpha \in [-\pi \sin s, \pi \sin s]} \{\cos^{-1}(-\alpha/\pi)-\cos^{-1}[(-\alpha + \phi_{md}/8)/\pi]\} = \cos^{-1}(\sin s)-\cos^{-1}(\sin s+ \phi_{md}/8\pi) \tag{4}$$

If the minimum attainable discrete delay is 0.1π and the required span is $S=\pi/6$, the minimum resolution of the array will be about 2°.

We require that

$$\phi_{md}/8 \leq \phi_{Mp} \tag{5}$$

to ensure that the phase shift between elements can be kept progressive. If (5) cannot be maintained, we shall have to use analog phase shifters in preceding stages, until the cumulative phase shift that they introduce is within the smallest step of the discrete phase shifter.

The minimum discrete phase shift attainable at 40 GHz is ~5°, resulting in a resolution of about 0.25° for a ±30° cone, and about 5° for 180° span.

Stochastic Effects An issue of major importance in array evaluation and design is the effect of nondeterministic deviations in array parameters on overall beam performance. Frequency jitter, as well as modulation, may cause direction jitter, and change the antenna pattern. Overall degradation may be caused by noise in the phase shifters, or by manufacturing inaccuracies (which can be statistically characterized).

In the optically controlled array, determination of nondeterministric effects involves the noises which are generated in the optical devices, their statistical characterization and the propagation of these noises through (nonlinear) input-output characteristics.

To exemplify these effects we shall consider again the linear 64 element array of figure 5, and concentrate on a 8-element subarray, whose progressive phase shift is determined by a piezoelectric ring according to equation (1).

We shall assume that the frequency f, the voltage V and the diameter D are normal random variables $f_g \sim N(f_o, \sigma_f)$, $V \sim N(V_o, \sigma_V)$, $D \sim N(D_o, \sigma_D)$. We then get that the progressive phase shift is a random variable with mean

$$E(\alpha) = \underline{K}\, f_o D_o\, V_o, \quad \underline{K} = (2\pi^2 \text{ x } 10^{-5})\,/v_g \tag{6}$$

and variance which can be approximated

$$(\sigma_\alpha)^2 = \underline{K}^2 (f_o{}^2 D_o{}^2\, \sigma_V{}^2 + V_o{}^2 D_o{}^2 \sigma_f{}^2 + f_o{}^2 V_o{}^2 \sigma_D{}^2) \tag{7}$$

Example For $f_o = 40$ GH$_z$, $D_o = 0.1$m and $V_o = 10$KV we get $E(\alpha) = 1.5°$.
Let $\sigma_D = 0.01$, $\sigma_V = 0.100$ KV and $\sigma_f = 40\text{x}10^6$ Hz, we get $\sigma_\alpha \sim 0.015°$

The effect of progressive shift inaccuracy on the direction can be calculated using [7, p. 174].

$$\sigma_\mu/\Delta_\mu \sim (3/M)^{1/2}\, (\sigma_\alpha/\pi) \tag{8}$$

where

M is the number of elements
Δ_μ is the 3 dB antenna bandwith
σ_α is the progressive shift standard deviation.

A note on optimization Finding the "best" system architecture for a hybrid system is expected to be a difficult problem which involves optimization with respect to a prescribed objective function. We consider the general problem of synthesizing a structure to be too complicated to formulate, and hence a proposed approach is to optimize several "basic" architectures (like architectures 1 and 2 in this paper) with respect to a single performance index, and compare values of the performance indices. Multivariate optimization of arrays with respect to a single objective function have been performed successfully for maximization of directivity, SNR and power gain (see [11] and its references). The challenge that the optically controlled array presents involves a multi-objective function with highly nonlinear constraints - particularly, constraints related to the conversions microwave/optical and optical/microwave.

Conclusion

The evolution of satellite communications into millimeter wave frequencies is in progress, and the large aperture phased array is expected to become a key element in this process. Recent advances in lightwave technology hold the promise of facilitating the realization of such arrays. We have presented some of the issues that array synthesis raises. The main challenge is to determine a technically-sound blend of microwave and optical subsystems that will constitute a viable alternative to mechanically steered dishes presently in use.

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