# Design for Steering Accuracy in Antenna Arrays Using Shared Optical Phase Shifters

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*Abstract*—**Uniform linear phased arrays where many radiating elements share a relatively small number of phase shifters are investigated. Such architectures arise in arrays which derive the time-delays in the signal paths from a small group of independent phase shifters. In particular, a true time-delay device which has been suggested recently for optically controlled arrays is used as the basic phase shifter. Different architectures, viz. alternative procedures of deriving the necessary time-delay for each antenna in the face of phase-shifter inaccuracies are examined. The variance of the steered beam's direction is used as the performance criterion. The direction-optimal architecture is obtained by means of quadratic programming, and is shown to be not unique. The nonuniqueness of the optimal architecture is exploited to improve other characteristics of the array's beam shape, and the optimal solution is shown to compare favorably with a suboptimal interleaved solution which is easier to implement.**

## I. Introduction

THE GROWING USE of phased antenna arrays in communications and radar has motivated many studies on the subject of beamshape characteristics in the face of inaccuracies in feeding and element location. The impact of gain and phase inaccuracies has been examined using various statistical models (e.g. [1]–[4] and their references.) A related topic of interest is the impact of errors in element location which occur in arrays that are mounted on nonflexible structures (e.g. [5], [6] and their references). In this paper we concentrate on beamsteering errors caused by phase inaccuracies in arrays where many antenna elements share the same phase shifter. Architectures of this kind are becoming popular in large arrays, due to mechanical and signal distribution constraints which large arrays must satisfy [7]. The large number of elements in millimeter-wave arrays and their high density preclude the use of a single independently controlled phase shifter per element. The alternative is to derive the time-delay of each signal path from a few phase shifters which can be "shared" in some sense. This sharing can be limited to the control signals which tune the individual phase shifters, or it can include the physical sharing of the delay line using novel techniques.

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### *The Basic Configuration*

We consider a uniform linear phased array with $n$ antenna elements, where the relative phase shift of the $k$th element with respect to the first is $(k-1)\,\alpha$ and $\alpha$ is the (controlled) progressive phase shift of the array (Fig. 1(a)). In this well-studied architecture, the beam's characteristics are controlled by the gains and phase shifts of the signals routed to the radiating elements. The novelty in the structure that we investigate is that it uses a small number of "shared" phase shifters in the signal distribution and phasing subsystem in order to shape the beam (Fig. 1(b)). The model of the shared phase shifter will follow the recently suggested optical true-time-delay phase shifter, which is based on a piezo-electric-crystal [8]. This device is used in optically controlled arrays. The microwave signals from the primary signal generator are converted to the optical domain, and are carried to the front-end monolithic microwave integrated circuits (MMICs) via optical fibers (Fig. 2). The fibers are wrapped in groups of four or eight around piezo-electric crystals, whose circumference is controlled by external dc voltage. Upon application of the control voltage, the circumference is elongated by an amount $\Delta L$, resulting in a delay of $\tau_k$ being introduced in the $k$th signal path (and a consequent phase shift)

$$\tau_k = \eta_k \frac{\Delta L}{v_g} \tag{1}$$

where $v_g$ is the speed of the optical signal in the fiber and $\eta_k$ is the number of winding of the $k$th fiber around the crystal. Fig. 3 depicts the phase shifter for four antennas. Direction control is facilitated through the dc voltages applied to the phase shifter. Figs. 4(a) and 4(b) show two architectures (corresponding to Figs. 1(a) and 1(b)) which provide phase shifting. In Fig. 4(a), all phase shifts are statistically uncorrelated due to the independence of the paths. In the configuration Fig. 4(b), paths that share the same phase shifter (such as the second and the third) have fully correlated phase errors while paths that use different phase shifters (such as the second and the fifth) are statistically uncorrelated. (If, in the extreme case, one crystal is used to control the phases of all the elements, the phase shifts become fully correlated.) The applicability of such an array in tasks that require beamsteering and target tracking relies on the accuracy that can be achieved in directing the beam to the desired location. This accuracy (measured in terms of statistical moments of the gain and the main direction)

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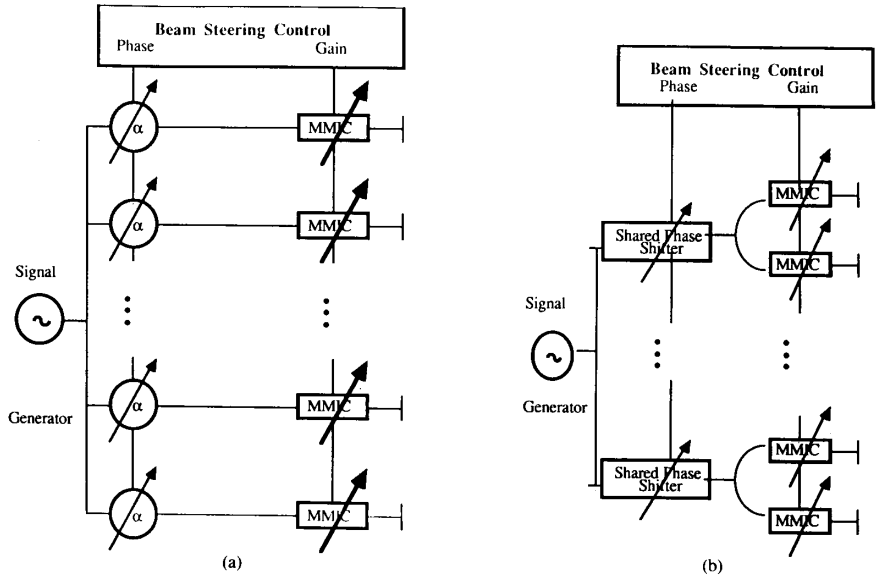


Fig. 1. (a) A steerable uniform linear array. (b) A steerable uniform linear array with shared phase shifters.

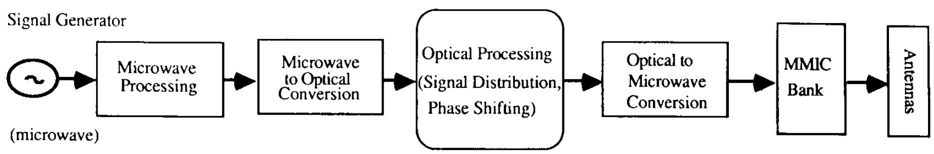


Fig. 2. An optically controlled phase array antenna system.

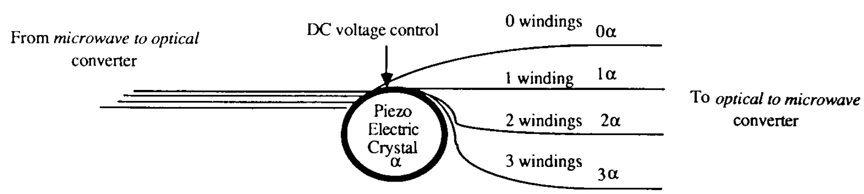


Fig. 3. A piezo-electric crystal-based phase shifter for four antennas.

depends on the statistical properties of the control voltages and the resulting phase shifts.

As many different architectures are possible with the same number of antennas and phase shifters, the situation calls for identifying the optimal array architecture with respect to a desirable beamshape. In particular, we shall seek an optimal configuration for a four-phase shifter, 16-element structure such as in Fig. 4, with respect to beamsteering accuracy (= variance of the main direction.)

## II. The Effects of Phasing Errors on Beam Direction

We consider the standard uniform linear array with $n$ nondirectional elements separated physically by a distance $d$. The normalized horizontal pattern is given by

$$E_T = \left| \sum_{k=0}^{n-1} I_k \exp\,(ik\Psi_k) \right| \qquad (2)$$

where

- $\Psi_k$ $\beta d \cos\phi + \alpha + \Delta\alpha_k = \Psi + \Delta\alpha_k$
- $\beta$ wavenumber $= 2\pi/\lambda$
- $\lambda$ wavelength
- $\phi$ the beam's direction
- $\alpha$ controlled progressive phase shift
- $\Delta\alpha_k$ error in the progressive phase shift introduced in the path to the $k$th radiating element
- $I_k$ signal gain at the $k$th radiating element.

The difference in the direction accuracies that can be achieved with different architectures lies in the interrelations between the deviations $\Delta\alpha_k$ ($k = 0, 1, 2, \cdots, n-1$). In a *fully correlated* architecture all the deviations $\Delta\alpha_k$ are the same random variable, while in a *fully uncorrelated* architecture (Figs. 1(a) and 4(a)) the phase deviations are $n$ independent random variables. Figs. 1(b) and 4(b) represent two of many *partially correlated* architectures in which some of the $\Delta\alpha_k$

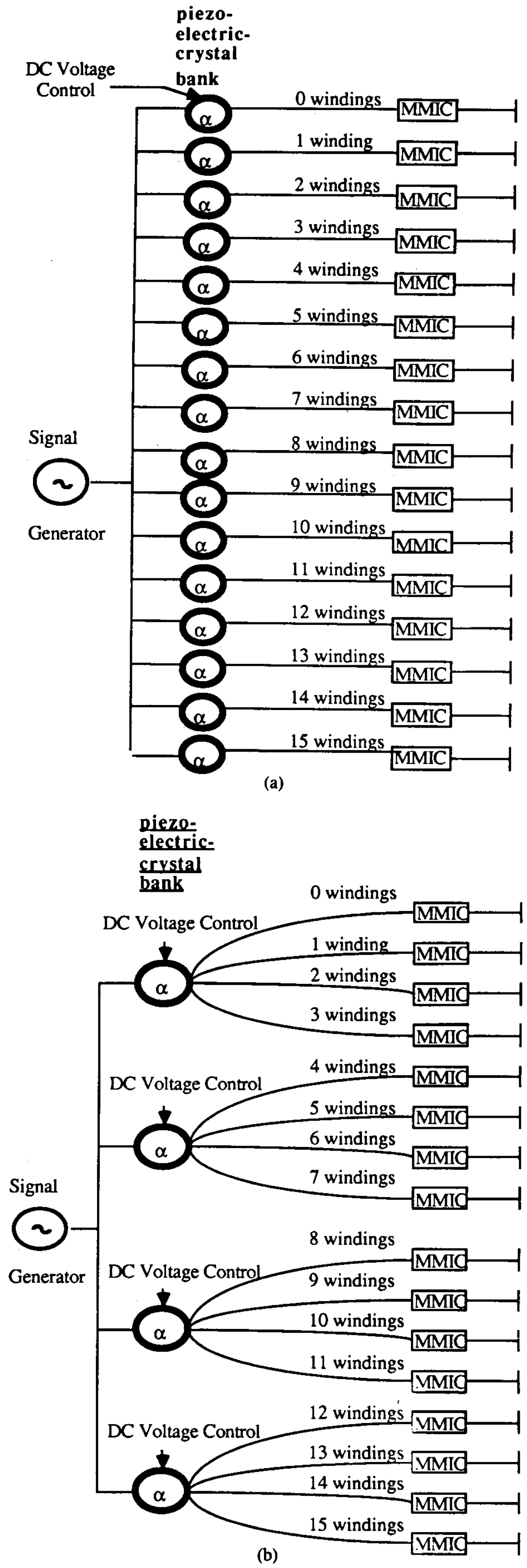


Fig. 4. (a) A 16-element architecture for an optically controlled array with 16 independent phase shifters. (b) A 16-element architecture for an optically controlled array with four shared phase shifters.

are identical. To find $\phi_{\max}$, the direction of the beam's maximum, we shall find the extrema of $|E|^2$.

$$|E|^2=\left[\sum_{k=0}^{n-1} I_k \cos (k\Psi_k)\right]^2+\left[\sum_{k=1}^{n-1} I_k \sin (k\Psi_k)\right]^2. \quad (3)$$

Evaluation of the total phase $\Psi$, which corresponds to the direction of the maximum, can be reduced to solving for $\Psi$ in the expression

$$\sum_{k=0}^{n-1}\sum_{j=0}^{n-1} I_k I_j j \sin [(k-j)\Psi+k\Delta\alpha_k-j\Delta\alpha_j]=0. \quad (4)$$

Equation (4) is obtained from (3) by equating the derivation of $|E|^2$ with respect to $\Psi$ to zero, and using standard trigonometric identities [9]. Assuming that the deviations $\Delta\alpha_k$ are small, and that the maximum corresponds to $\Psi \approx 0$, we can approximate (4) by

$$\sum_{k=0}^{n-1}\sum_{j=0}^{n-1} I_k I_j j[(k-j)\Psi+k\Delta\alpha_k-j\Delta\alpha_j]=0 \quad (5)$$

which admits a solution for $\Psi$ which is linear in the phase deviations

$$\Psi=\frac{-\sum_{k=0}^{n-1}\sum_{j=0}^{n-1}(k\Delta\alpha_k-j\Delta\alpha_j)I_k I_j j}{\sum_{k=0}^{n-1}\sum_{j=0}^{n-1} I_k I_j (k-j) j} \quad (6)$$

which we rewrite as

$$\Psi=\sum_{k=0}^{n-1}\gamma_k\Delta\alpha_k \quad (7)$$

where

$$\gamma_k=\frac{\sum_{j=0}^{n-1} I_k I_j k(j-k)}{\sum_{k=0}^{n-1}\sum_{j=0}^{n-1} I_k I_j j(k-j)}. \quad (8)$$

For the case where $I_k \equiv 1$ (uniform window) we have for (8)

$$\gamma_k=\frac{12kn\left(\frac{n-1}{2}-k\right)}{-n^4+n^2}. \quad (9)$$

Let the distribution system consist of $m$ phase shifters (in Fig. 4(b), $m = 4$). We shall assume that the phase shift introduced in any signal path is a linear combination of the phase shifts introduced by each phase shifter, indicating that a fiber may wrap around each crystal any number of times as long as the desired total phase in each path is realized. Let $a_{kj}$ be the number of windings that the $k$th fiber makes around the $j$th phase shifter. Then

$$\Delta\alpha_k=\sum_{j=1}^{m} a_{kj}\Delta\delta_j \quad (10)$$

where $\Delta\delta_j$ is the error in the phase shift introduced (per one winding) by the $j$th phase shifter, as a result of a deviation from the desired $\Delta L$ in (1). Equation (7) hence becomes

$$\Psi = \sum_{j=1}^{m} \sum_{k=0}^{n-1} \gamma_k a_{kj} \Delta\delta_j. \tag{11}$$

Assuming that the deviations $\Delta\delta_j$ are independent, identically distributed random variables with zero mean and variance $\sigma_\delta^2$, minimization of the variance of $\phi_{\max}$ is equivalent to the minimization of the variance of $\Psi$,

$$\sigma_\Psi^2 = \sigma_\delta^2 \sum_{j=1}^{m} \left( \sum_{k=0}^{n-1} \gamma_k a_{kj} \right)^2 \tag{12}$$

over the matrix $[A] = \{a_{ij}\}$, and under the constraint

$$\sum_{j=1}^{m} a_{kj} = k. \tag{13}$$

The constraint guarantees that a uniform linear array is obtained. The achitecture synthesis problem involves standard least squares optimization which is independent of the value of $\sigma_\delta^2$.

## III. Comparison of Architectures: The Principle of Interleaving

There are many possible choices for $\{a_{kj}\}$ under the constraint (13). The architecture depicted in Fig. 4(a) represents the choice $A_1$ in (14a) which calls for four independent subarrays.

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 5 & 0 & 0 \\ 0 & 6 & 0 & 0 \\ 0 & 7 & 0 & 0 \\ 0 & 0 & 8 & 0 \\ 0 & 0 & 9 & 0 \\ 0 & 0 & 10 & 0 \\ 0 & 0 & 11 & 0 \\ 0 & 0 & 0 & 12 \\ 0 & 0 & 0 & 13 \\ 0 & 0 & 0 & 14 \\ 0 & 0 & 0 & 15 \end{bmatrix} \tag{14a}$$

$$A_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 \\ 2 & 1 & 1 & 1 \\ 2 & 2 & 1 & 1 \\ 2 & 2 & 2 & 1 \\ 2 & 2 & 2 & 2 \\ 3 & 2 & 2 & 2 \\ 3 & 3 & 2 & 2 \\ 3 & 3 & 3 & 2 \\ 3 & 3 & 3 & 3 \\ 4 & 3 & 3 & 3 \\ 4 & 4 & 3 & 3 \\ 4 & 4 & 4 & 3 \end{bmatrix}. \tag{14b}$$

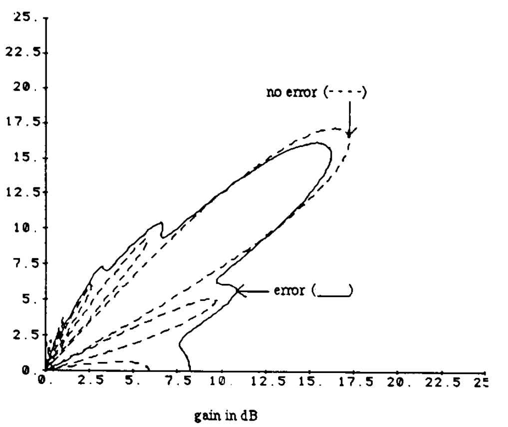


Fig. 5. A comparison of the average field patterns generated by the standard $A_1$ architecture with and without phase errors ($\sigma_\delta = 0.035\alpha$).

TABLE I
COMPARISON OF NORMALIZED VARIANCES IN MAIN DIRECTION FOR STANDARD AND INTERLEAVED ARCHITECTURES

| Number of Phase Shifters | 2 | 4 | 6 | 8 |
|---|---|---|---|---|
| Standard Architecture | 250 | 185 | 103 | 102 |
| Interleaved Architecture | 113 | 57 | 38 | 29 |

Inside each array, there is a high degree of correlation between adjacent elements. Fig. 5 compares the average beamshape corresponding to $A_1$ to the error-free beamshape. Clearly, the phase-shift errors (with $\sigma_\delta = 0.035\alpha$) introduce a severe degradation in main-direction gain and in sidelobe level. This degradation raises the possibility of varying the architecture by changing routes of the fibers to the antenna elements. One possible variation on architecture $A_1$ would involve the routing of a fiber around more than one crystal. In particular, a possible routing strategy would call for progressively moving from crystal to crystal, using one wrapping at a time until the necessary phase shifting has been accumulated for each antenna. This arrangement in the 16-element, four phase-shifter case is represented by the matrix $A_2$ in (14b). The normalized performance index (12) (with $\sigma_\delta^2 = 1$) is 185 for $A_1$, and a significantly smaller 56.7 for $A_2$. The "spreading" of the path among the different sources of error so as to "even" the effects of phase inaccuracies is similar to *interleaving* procedures used in coding (e.g. [10]). The reduction in direction-steering error in the architecture is a consequence of the independence of errors in different phase shifters, which causes partial error cancellation in the process of beam formation. In Table I we compare the normalized variance of $\Psi$, ((12), $\sigma_\delta^2 = 1$) using the standard architecture $A_1$ to the variance resulting from the interleaved architecture $A_2$. The comparison is conducted with two, four, six, and eight phase shifters in the 16-element array, and the advantage of the interleaved architecture is clear.

In Fig. 6 we depict the average beam shape of a four-phase shifter, 16-element array using the standard and interleaved architectures. Evidently the average interleaved beam shape is

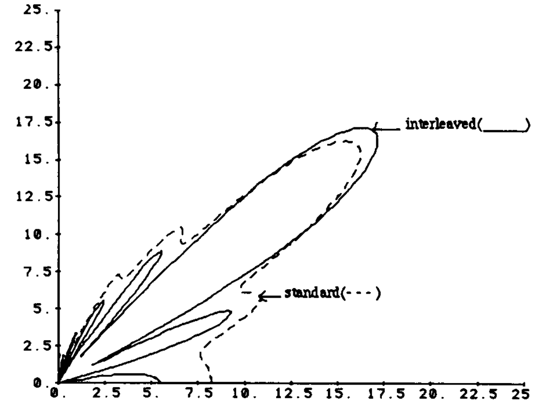


Fig. 6. A comparison of the average field patterns generated by standard ($A_1$) and interleaved ($A_2$) architectures ($\sigma_\delta = 0.035\alpha$).

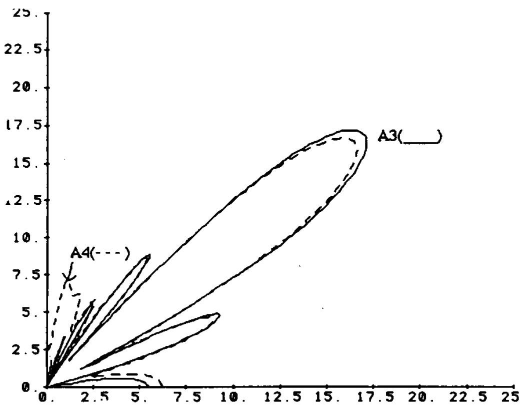


Fig. 7. A comparison of the average field patterns generated by two direction-optimal architectures ($A_4$ and $A_5$) ($\sigma_\delta = 0.035\alpha$).

considerable sharper, a result of smaller direction-fluctuations due to reduced phasing errors.

## IV. Synthesis of Direction—Optimal Solution

The minimization problem of (12), (13) is a linearly constrained, nonlinear optimization problem which can be solved via the method of Lagrange multipliers where

$$F(a_{kj})=\sigma_\delta^2\left(\sum_{j=1}^{m}\left(\sum_{k=0}^{n-1}\gamma_k a_{kj}\right)^2\right)$$

(objective function in $nm$ variables) (15)

$$H_k(a_{kj})=\left(\sum_{j=1}^{m}a_{kj}\right)-k=0 \quad (n \text{ constraint functions}). \quad (16)$$

by solving the Lagrange equation:

$$\nabla_{a_{kj}}F(a_{kj})+\sum_{i=0}^{n-1}\lambda_i\nabla_{a_{ij}}H_i(a_{ij})=0 \quad (17)$$

we can find those Lagrange multipliers $\lambda_i\ i=0,\cdots,n-1$ such that the objective function is minimized subject to the given constraints $H(a_{kj})$. The Lagrange multipliers are given by

$$\lambda_i=\frac{-2\sigma_\delta^2\gamma_i\sum_{k=0}^{n-1}k\gamma_k}{m}. \quad (18)$$

From (17) and (18) we find that the necessary condition for a minimum of (15) is given by

$$\sum_{k=0}^{n-1}\gamma_k\left(a_{kj}-\frac{k}{m}\right)=0, \qquad \text{for all } j=1,2,\cdots,m \quad (19)$$

with the additional inequality constraints $a_{kj}\geq 0$. From (19) it is obvious that there are many optimal solutions to (15). In the appendix we present five such optimal solutions for the 16-element, four-phase shifter architecture. The normalized performance index for all of the optimal solutions in this case is 56.3, which is not a significant improvement over the interleaved solution's value of 56.7. The solutions in the Appendix are more difficult to implement than the interleaved solution due to the entries being noninteger. The availability of several direction-optimal solutions to (15), (16) allows for the selection of an architecture which, in addition to having the minimum direction-variance, possesses other desirable features. In Fig. 7 we compare the average beamshapes for two of the solutions to this example ($A_3$ and $A_4$). The direction-optimal solutions do not yield the same field patterns. We choose the solution whose performance is as similar as possible to the error-free pattern. The performance criterion is the squared error, measured by the area difference between the direction-optimal pattern and the error-free pattern. In Table II we show the squared error for architectures $A_1$ and $A_7$. The data are presented in order of increasing squared error.

TABLE II
COMPARISON OF ARCHITECTURES

| Architecture | Normalized Performance Index (12) | Squared Error |
|---|---|---|
| $A_3$ | 56.25 | 5.23 |
| $A_2$ (interleaved) | 56.68 | 5.28 |
| $A_4$ | 56.25 | 5.97 |
| $A_7$ | 56.25 | 12.0 |
| $A_8$ | 56.25 | 14.8 |
| $A_5$ | 56.25 | 23.2 |
| $A_1$ (standard) | 185.0 | 55.3 |

The $A_3$ architecture performs the best of all studied architectures in terms of both the normalized performance index and the squared error. This architecture corresponds to the solution:

$$a_{kj}=\frac{k}{m} \quad (k=0,1,2,\cdots,n-1) \quad (j=1,2,3,\cdots,m). \quad (20)$$

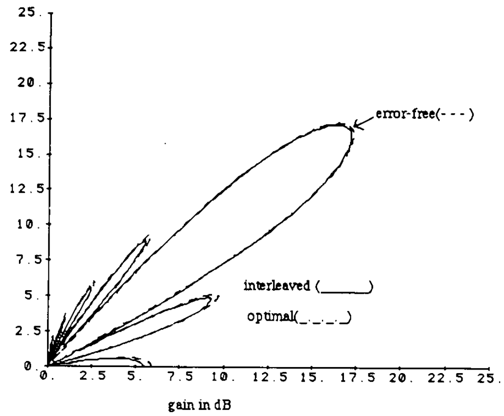


Fig. 8. A comparison of the average field patterns generated by the error-free architecture, the direction-optimal architecture ($A_4$) and the interleaved architecture ($A_2$) ($\sigma_\delta = 0.035\alpha$).

From Table II we see that the *interleaved* solution (14b) is nearly optimal both in terms of direction-variance and squared error. In Fig. 8 we compare the direction-optimal solution $A_3$ with the *interleaved* solution $A_2$ and to the error-free field. The $A_3$ beamshape and the interleaved beamshape are virtually indistinguishable, a fact which suggests that the ease of implementation may warrant the use of the *interleaved* scheme instead of the direction-optimal arrangement.

## V. Conclusion

We have demonstrated that beamsteering errors in shared-phase-shifter array architectures can be reduced significantly by the use of an appropriate sharing scheme. The model that we adopted for the demonstration of this procedure is applicable for optically controlled arrays as well as for other systems which use decentralized phase-shifter control. The best noise-resistant architecture, resulting from the steering-error minimization, divides the error contribution as evenly as possible between the statistically independent inaccuracy sources. The non-uniqueness of the solution allows for the selection of direction-optimal architectures which have additional desirable beam features. Additionally, we have shown that there exists a suboptimal solution, the *interleaved* architecture, which is easier to implement than the optimal solution and performs nearly equally well.

## Appendix

Five direction-optimal architectures for the $16 \times 4$ antenna array

$$A_3 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0.25 & 0.25 & 0.25 & 0.25 \\ 0.5 & 0.5 & 0.5 & 0.5 \\ 0.75 & 0.75 & 0.75 & 0.75 \\ 1 & 1 & 1 & 1 \\ 1.25 & 1.25 & 1.25 & 1.25 \\ 1.5 & 1.5 & 1.5 & 1.5 \\ 1.75 & 1.75 & 1.75 & 1.75 \\ 2 & 2 & 2 & 2 \\ 2.25 & 2.25 & 2.25 & 2.25 \\ 2.5 & 2.5 & 2.5 & 2.5 \\ 2.75 & 2.75 & 2.75 & 2.75 \\ 3.0 & 3 & 3 & 3 \\ 3.25 & 3.25 & 3.25 & 3.25 \\ 3.5 & 3.5 & 3.5 & 3.5 \\ 3.75 & 3.75 & 3.75 & 3.75 \end{bmatrix} \qquad A_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0.2 & 0.2 & 0.2 & 0.4 \\ 0.5 & 0.5 & 0.5 & 0.5 \\ 0.75 & 0.75 & 0.75 & 0.75 \\ 0 & 1.25 & 1.25 & 1.5 \\ 0 & 1.56 & 1.56 & 1.88 \\ 1.5 & 1.5 & 1.5 & 1.5 \\ 1.75 & 1.75 & 1.75 & 1.75 \\ 2 & 2 & 2 & 2 \\ 2.25 & 2.25 & 2.25 & 2.25 \\ 2.5 & 2.5 & 2.5 & 2.5 \\ 2.59 & 2.59 & 2.59 & 3.22 \\ 2.88 & 2.88 & 2.88 & 3.38 \\ 3.25 & 3.25 & 3.25 & 3.25 \\ 3.5 & 3.5 & 3.5 & 3.5 \\ 3.6 & 3.9 & 3.9 & 3.55 \end{bmatrix}$$

$$A_5 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 2 \\ 0 & 0 & 0 & 3 \\ 4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 5 \\ 0 & 0 & 0 & 6 \\ 0 & 0 & 0 & 7 \\ 8 & 0 & 0 & 0 \\ 0 & 6 & 3 & 0 \\ 0 & 0 & 0 & 10 \\ 6 & 0 & 0 & 5 \\ 0 & 0 & 7.07 & 4.93 \\ 0 & 1.07 & 11.93 & 0 \\ 0 & 5.47 & 0 & 8.53 \\ 9.49 & 5.51 & 0 & 0 \end{bmatrix} \qquad A_6 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 2 \\ 0 & 0.29 & 0.29 & 0.43 \\ 0 & 0 & 1 & 3 \\ 1 & 0 & 0 & 4 \\ 1.5 & 0 & 0.5 & 4 \\ 0 & 0 & 1.75 & 5.25 \\ 1.38 & 0 & 2 & 4.63 \\ 4.25 & 0 & 0 & 4.75 \\ 2.28 & 0 & 3.22 & 4.5 \\ 0.356 & 0.5 & 3.64 & 6.5 \\ 0 & 0.93 & 4.22 & 6.85 \\ 0.26 & 1.96 & 3.9 & 6.88 \\ 0.89 & 9.05 & 5.05 & 0 \\ 0.89 & 9.05 & 5.05 & 0 \end{bmatrix}$$

$$A_7 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 2 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 4 \\ 0 & 0 & 0 & 5 \\ 0 & 0 & 0.41 & 5.59 \\ 0 & 0 & 2.13 & 4.87 \\ 0 & 0 & 2.38 & 5.63 \\ 7.34 & 0 & 1.66 & 0 \\ 5.73 & 0 & 2 & 2.27 \\ 0 & 5.15 & 2.5 & 3.35 \\ 0 & 5.83 & 0 & 6.17 \\ 0 & 1.83 & 4.92 & 6.25 \\ 11.35 & 1.59 & 1.06 & 0 \\ 0 & 4.68 & 5.86 & 4.46 \end{bmatrix}.$$

## Nomenclature

- $\alpha$ Progressive phase shift between elements.
- $\beta$ Wavenumber $= 2\pi/\lambda$.
- $\gamma_k$ Weighting of $\Delta\alpha_k$ in determining the total phase shift $\Psi$.
- $\Delta\alpha_k$ Error in the progressive phase shift introduced in the path to the $k$th radiating element.
- $\Delta\delta_j$ Phase error introduced by the $k$th phase shifter.
- $\eta$ Number of times a fiber is wrapped around a crystal.
- $\lambda$ Wavelength.
- $\lambda_i$ Lagrange multiplier.
- $v_g$ Speed of the optical signal in the fiber.
- $\phi$ Beam's direction.
- $\Psi$ Total phase shift.
- $a_{ij}$ Matrix element equal to the number of times the $i$th fiber is wrapped around the $j$th crystal.
- $d$ Separation between elements.
- $E_T$ Normalized horizontal field pattern.
- $\Delta L$ Change in fiber length.
- $n$ Number of antenna elements.
- $\tau_k$ Time-delay introduced in the $k$th signal path.

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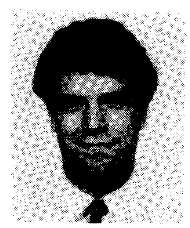


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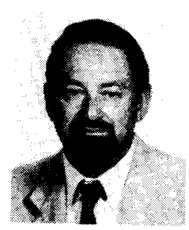


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Dr. Herczfeld has published over 120 papers in solid-state electronics, microwaves, solar energy, and biomedical engineering. He has taught 20 different courses at the graduate and undergraduate levels, and lectured extensively in the United States and in ten other countries. He is a member of APS, SPIE, and the International Solar Energy Society, and a recipient of several research awards.