Optically Generated True-Time Delay in Phased-Array Antennas

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***Abstract*—This tutorial review paper deals with various methods for solving a basic problem of wideband phased arrays, i.e. beam squinting, using optical technologies. The problem of beam squinting in phased arrays is analyzed and the concept of true-time delay is introduced. The advantages of realizing variable delay lines by optical rather than by microwave means are reviewed, together with principles of operation. Among the techniques described are switched-path length delay lines, fiber stretchers, tunable lasers with highly dispersive fiber, and coherent techniques incorporating dispersive delay. Recent experimental results are discussed in the light of practical system requirements.**

I. INTRODUCTION

PHASED ARRAY antennas have a significant role to play in high performance radar and communication systems. By realizing the illumination of a large virtual aperture via a multitude of small discrete radiating elements, the beam pointing direction can be varied (electronically). For this purpose, the phase of the exciting signal of consecutive radiators has to be varied appropriately. Air surveillance radars and SDMA-SS (Space Division Multiple Access-Satellite Switched) systems are among potential applications of phased arrays.

Although the theory and techniques of phased arrays have long since been developed and are well documented (e.g. [1], [2]), the application of large arrays has been impeded by practical difficulties: the feed system of an array of, say, thousands of elements containing thousands of phase shifters and connecting lines, power splitters, etc. is so robust, heavy, inflexible and expensive as to rule out their application in many instances. The evolution of optical techniques, and in particular optical transmission/processing of microwave signals, is one factor in solving these practical problems [3], [6]. In optical beam forming systems, excited signals are converted to the optical band, transmitted via optical fibers, and reconverted to the microwave band at the radiators. Optical signals are also used to control circuit elements such as phase shifters and attenuators. This approach presumes active radiating elements that can increasingly be realized in low-cost MMIC technology.

Wideband phased arrays raise particular problems. If the array is fed by wideband signals and a constant phase shift is produced from element to element, the beam pointing is different for different frequency components—a phenomenon called *beam squinting.* The effect is even more pronounced if the essentially wide-band characteristic of the optical beamforming network is to be exploited and phased arrays in more than one frequency band use the same network. Bandwidth considerations of phased arrays were treated in the early years of phased-array technology and a full theory is given in the first edition of Skolnik's *Radar Handbook* [7]. It turns out that this squint can be compensated for by using delay lines rather than phase shifters. The delay values have to be variable as *scanning antennas* are to be produced. From the practical realization point of view, wide-band arrays applying variable delay lines are even more difficult than arrays with phase shifters. Here again, optical processing offers a favorable alternative. In recent years, numerous publications have attacked this problem and have shown that optical beam forming may result in practical realizations of wide-band phased arrays.

In this tutorial review paper, optical methods for the realization of variable time delay are presented, together with a comparison of various solutions. The organization of the paper is as follows. Section II contains a brief discussion of wide-band phased arrays and, in particular, of beam squinting and the concept of true time delay for solving this problem is elaborated. Section III deals with optical realization principles. In Section IV various optical solutions are described. Finally results are discussed in Section V and some conclusions are drawn.

II. BANDWIDTH CONSIDERATIONS IN PHASED ARRAYS: THE CONCEPT OF TRUE TIME DELAY

As already mentioned and as discussed, e.g., in [1, vol. 2] in phased-array antennas beam steering is achieved by the application of appropriate progressive phase difference in the excitation of radiating elements. In this case the antenna beam maximum is pointed toward ϑ_0

$$\vartheta_0 = \sin^{-1}\left(\frac{\lambda}{y}\frac{\psi}{2\pi}\right) \tag{1}$$

where y is the location of the particular radiating element being investigated, λ is the wavelength and, ψ the phase of the signal at radiating element located at y.

Thus, to obtain a fixed angle ϑ_0, phase shift ψ has to be proportional to the element location y. Or, with given ϑ_0, the

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excitation of the element at point y has to have the phase

$$\psi = 2\pi \frac{y}{\lambda} \sin \vartheta_0. \tag{2}$$

Equation (2) does not cause any difficulty, in principle, with the realization of the appropriate phase shifts as long as the signal to be transmitted or received can be regarded as *monochromatic,* i.e. its band-width is much less than the carrier frequency. Moreover, phase-shift ψ has then only to be realized in the mod (2π) sense. In the case of wide-band signals, however, the beam will be "squinted": components of different frequency will be radiated in different directions. The essentially narrow-band character of a *phased* array can be discovered if frequency rather than wave-length is substituted in (1) and (2)

$$\vartheta_0 = \sin^{-1}\left(\frac{c}{y}\frac{\psi}{2\pi f}\right) \tag{3}$$

$$\psi = 2\pi \frac{y}{c} f \sin \vartheta_0 = \frac{\omega y}{c} \sin \vartheta_0 \tag{4}$$

with c the velocity of the electromagnetic waves and f and ω the frequency and angular frequency, respectively.

From (3), it can be seen that changing the frequency results in the change in ϑ_0.

Beam squinting results in linear distortion of the signal if received at a particular distant spot in direction ϑ_0 as attenuation of higher-frequency components of the signal will be increased as a result of the diminishing value of the antenna pattern $G[\vartheta_0(f)]$.

From (3) and (4), several approximate design criteria can be obtained [7]. For example, if a maximum scan angle of 60° is required

$$B^{\%} = BW^{0} \tag{5}$$

with $B^{\%}$ the percentage band-width and BW° the bore-sight beam width of the array measured in degrees.

On the other hand, (4) gives the solution to making the array broad-band: phase-shift has to be proportional to the frequency, i.e. time-delay rather than phase-shift has to be applied between elements. By so doing, each frequency component will be radiated in the same direction. Thus, for wide-band signal processing, the term "timed-array" would be more appropriate than phased array. The operation needed for this result is called *true-time delay.* A detailed discussion of true-time delays in antennas can be found—among others—in [25] and [26].

Consider a signal

$$s(t) = Re[a(t)e^{j\omega_c t}] \tag{6}$$

where the representation via the real part of the analytic signals has been applied in order to show explicitly that $s(t)$ is a *modulated* signal. Here Re stands for the "real part of," $a(t)$ is the complex envelope of the signal, and ω_c is the carrier angular frequency.

In the frequency domain we have

$$S(\omega) = \frac{1}{2}\left[A(\omega - \omega_c) + A^*(-\omega - \omega_c)\right] \tag{7}$$

where $A(\omega) = \mathcal{F}[a(t)]$, the Fourier-transform of $a(t)$ and with $\mathcal{F}$ designating Fourier transform and * the complex conjugate.

By applying a constant phase shift ψ

$s_{ps}(t) = \mathrm{Re}[e^{j\psi}a(t)e^{j\omega_c t}]$ and

$$s_{ps}(\omega) = \frac{1}{2}[A(\omega - \omega_c)e^{j\psi} + A^*(-\omega - \omega_c)e^{-j\psi}] \tag{8}$$

where the subscript ps stands for "phase shifted."

In the actual case, however, the phase shift has to be proportional to the frequency, more particularly: ψ_0 is appropriate at ω_c and at other frequencies a differential phase shift, proportional to frequency difference, has to be applied. Thus the phase shift versus frequency can be expressed as

$$\psi(\omega) = \psi_0[1 + (\omega - \omega_c)/\omega_c] = \psi_0\omega/\omega_c. \tag{9}$$

This phase shift can be achieved by the use of a time delay

$$\tau \mathrel{\hat{=}} \frac{d\psi}{d\omega} = \psi_0/\omega_c. \tag{10}$$

Delay τ in frequency domain corresponds to

$$S_{ts}(\omega) = \frac{1}{2}[A(\omega - \omega_c)e^{j\omega\tau} + A^*(-\omega - \omega_c)e^{-j\omega\tau}] \tag{11}$$

where the subscript ts stands for "time shifted."

The magnitude of τ can be expressed as

$$\tau = d\psi_0/d\omega|_{\omega=\omega_c} = \frac{y}{c} \sin \vartheta_0. \tag{12}$$

Thus, the maximum time delay needed depends both on the maximum beam position angle and on the length of the array (L)

$$\tau_{\max} = \frac{L}{c} \sin \vartheta_{\max}. \tag{13}$$

It can be seen from the above that the array can be made wide-band if time delay rather than phase shift is applied, and that this delay has to be varied according to beam steering.

A fixed time delay can be realized by various methods, depending on the frequency band. The most self-evident realizations at microwave or optical frequencies are transmission lines, waveguides or free-space propagation. Normally, the signal has to be transmitted through a line having length

$$x = v\tau = \frac{v}{c} y \sin \vartheta_0 \tag{14}$$

with v the phase velocity of propagation in the line—usually being less than c.

To obtain some practical values let us take a large array, say a linear one of $L = 20$ m (e.g., one operating at 3 GHz with 400 $\lambda/2$ spaced radiators) a delay variation of 57.7 nsec is needed. Applying coaxial cables as feed lines (or any other slow wave structures) or assuming typical dielectric waveguides in the case of optical realizations $v/c = .7$ can be taken; this results in feed line length variable between limits of x_0 and $x_0 + 12$ m (!) in the case of $\vartheta_{\max} = 60°$. And, as beanwidth of this array is about .25° in the appropriate plane, true time delay has to be applied if the signal band-width exceeds 7.5 MHz.

From the above examples, it can be seen that delay networks can be rather complex and therefore expensive; realization can be eased by combining the *timed array* principle with the more conventional *phased array* [7]. The total array is partitioned into sub-arrays; *timing* is applied in feeding the sub-arrays, with *phasing* in the excitation of the individual radiators. Squinting in the sub-arrays is negligible, due to their reduced size. Some of the designs to be discussed use this principle of array partitioning.

III. OPTICAL VARIABLE TIME DELAY PRINCIPLES

To achieve variable time delay the electrical length of the line has to be varied, in accordance with (14). There are at least three advantages in realizing variable time delay beam forming networks for wide-band phase arrays in the optical domain: 1) the size and weight of the network is orders of magnitude less than that of its microwave or millimeter wave counterparts; 2) there is virtually no restriction in the length of the lines and of the frequency band and bandwidth [3] (due to low loss and essentially wideband characteristics of the components); and there is virtually no leakage of the signals in some solutions and a controllable leakage in other ones—one of the main practical problems in electrical realizations [7].

In searching for operating principles leading to optical variable delay networks, one has to take into account that *line lengths* have to be present and the *electrical length* has to be varied. In each practical solution reported, *light intensity* is modulated by the electrical signal, transmitted through the optical delay system and reconverted or converted to the microwave or millimeter wave band.

Thus far, three principles have been found that can be used for the purpose of variable delay:

1) The optical signal containing wide-band microwave modulation passes through optical paths of different physical length; this length-difference can be achieved by various means, including a set of switched lines of differing lengths—the optical analog of a digitally switched electrical transmission line.
2) This signal is transferred through *one* line, the length of which is mechanically varied.
3) Lines with extremely dispersive character are used and the optical frequency is varied.

From the optical point of view, direct modulation and heterodyne realizations are possible. Also, in some cases the optical waveguides are replaced by free-space sections of commensurate lengths.

Heterodyning offers features of special interest. As is well known, heterodyning of two optical signals can be achieved if two optical signals of identical polarization are summed and applied to a photodetector. Let one of the signals be

$$E_1(t) = \hat{E}_1 \cos[(\omega_o + \omega_c)t + \varphi] \tag{15}$$

and the other

$$E_2 = \hat{E}_2 \cos \omega_o t. \tag{16}$$

with ω_o the optical angular frequency, ω_c the (microwave) carrier frequency, and $\hat{E}_1$ and $\hat{E}_2$ the peak electric fields of signal 1 and 2, respectively.

The output current of the photodetector due to $E_1 + E_2$ is proportional to the envelope-squared of this signal; thus it can be given as

$$I = 2R\sqrt{P_1 P_2}\cos(\omega_c t + \varphi) + DC \text{ terms} \tag{17}$$

where R is the responsivity of the photodetector and P_1 and P_2 are the powers of signal 1 and 2, respectively. It can be seen that the *optical* phase shift is maintained in the *electrical* signal.

More generally, if the signal $a(t)$ modulates an optical carrier of frequency $\omega_o + \omega_c$ is delayed by τ, its Fourier transform can be written as

$$S(\omega) = \frac{1}{2}[A(\omega - \omega_o - \omega_c)e^{j\omega\tau} + A^*(-\omega - \omega_o - \omega_c)e^{-j\omega\tau}]. \tag{18}$$

The particular form of heterodyning applicable to optical detectors as mixers requires convolving the first term in (18) by $\delta(\omega + \omega_o)$ and the second term by $\delta(\omega - \omega_o)$. This results in

$$S_\mu(\omega) = \frac{1}{2}[A(\omega - \omega_c)e^{-j(\omega+\omega_o)\tau} + A^*(-\omega - \omega_c)e^{j(\omega-\omega_o)\tau}] \tag{19}$$

designating the microwave signal by the subscript μ. From (19) and (17) it is seen that the required delay *can* be realized at optical frequencies.

Writing $\omega\tau = \omega_c\tau + \Delta\omega\,\tau$, the phase shift required at the carrier frequency corresponding to the first term can be realized by a (short) optical line of length

$$\xi = \frac{\omega_c}{\omega_o}\frac{v}{c}\,y\sin\vartheta_0. \tag{20}$$

To realize the differential phase shift of the second term, either an (optical) section of the length x of (14) or and in some cases, preferably, a frequency-dependent path-length of

$$\Delta\xi = \frac{\Delta\omega}{\omega_c}\,\xi\left(1 - \frac{\omega_c}{\omega_o}\right) \tag{21}$$

has to be inserted. Note that while x is in the range of microwave wavelengths, $\xi + \Delta\xi$ is in the optical wavelength domain. The derivation of (21) is given in the Appendix.

IV. OPTICAL METHODS OF REALIZING TRUE TIME DELAY

A. Delay Line Switching [8], [9], [10], [27]

The most obvious method of realizing variable optical delay is to prepare a bank of optical fibers of the appropriate lengths and to choose the desired one by switching. Although both heterodyning and nonheterodyning designs could use this principle, each of the cited networks use the latter approach.

The switching method is perhaps the main concern in such schemes. In [9] and [10] each optical beam forming network contains N delay lines, i.e. N fibers of different length (in [10] $N = 8$, with delays $\tau_0 + 0, \tau_0 + \tau, \ldots \tau_0 + 7\tau$, representing a 3-bit time shifter), illuminated by N lasers. Each laser is fed through a bias switching diode, one laser is switched on, and $N - 1$ are switched off at an instant, according to the required

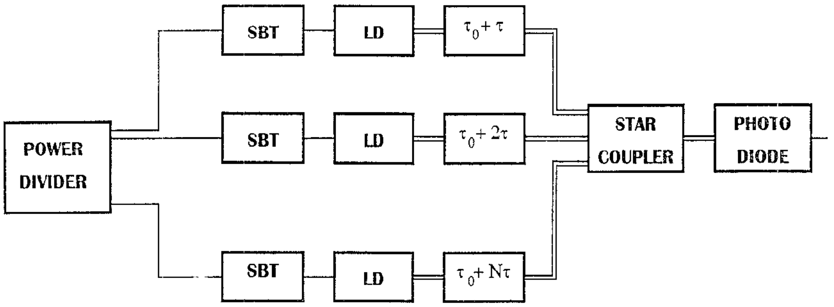

Fig. 1. True-time delay network using switched lasers and fibers of appropriate length.

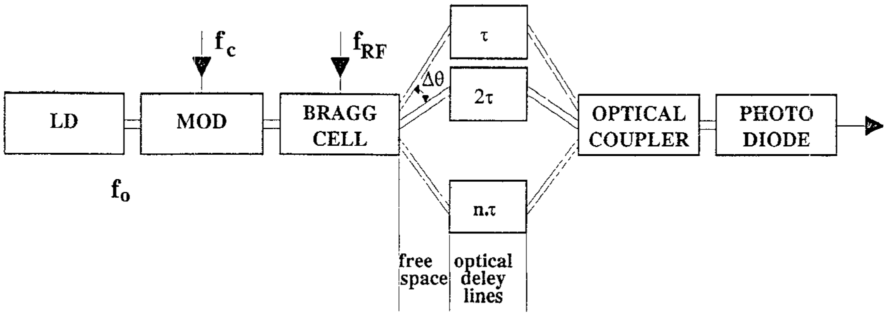

Fig. 2. True-time delay network using acustooptic deflector driven variable-frequency rf signal as optical switch.

delay value. The fibers are connected to the inputs of a star coupler, the output of which illuminates a photodetector. The lasers are directly modulated by the microwave signal, fed to them by a microwave $1/n$ power splitter. The architecture of the array was—as described briefly in Section III and in detail in [7]—a set of sub-arrays. A schematic drawing of the optical true-time-delay network is shown in Fig. 1. The array operates in two frequency bands: L band (1-2.6 GHz) and X band (8–12 GHz); a laser relaxation oscillation frequency of about 7 GHz was carefully selected to give maximum signal-to-noise ratio. Measured radiation peaks in the two frequency bands were pointed virtually in the same direction, even with steering of up to 24°, but side lobe levels did increase in this case to about -8 dB.

Reference [8] describes a different architecture where an optical rather than an electrical switch selects the appropriate delay line. the modulated optical signal is fed to a Bragg-cell beam deflector, the deflection angle being adjusted by the frequency of an acoustic RF drive signal. Fibers of different lengths according to the delay to be achieved are placed at appropriate angles, measured from the deflector central point. (See Fig. 2.) The fiber outputs are, as in the previous case, connected to an optical power combiner (a star coupler), and a photodetector. Switching is thus accomplished by the acoustooptic beam deflection. It is shown that

$$\Delta\vartheta = \frac{\lambda}{n\,V_s}\,\Delta f \tag{22}$$

with λ the optical wavelength, V_s the velocity of acoustic propagation, n the refractive index of the acoustooptic medium, and Δf the change of the drive signal frequency.

The main performance parameters of this switch according to [8] are microwave loss and coupling between adjacent light beams. Loss is estimated to be of the order of 6–10 dB.

Coupling between adjacent beams determines the minimum $\Delta\vartheta$ and thus the maximum number of outputs (i.e. of the delay lines). Given the required isolation I, the number of outputs is given as

$$N = \frac{4.6}{I^{1/2}}\,\frac{\Delta\vartheta}{\vartheta} \tag{23}$$

with I measured in dB and ϑ being the diffraction angle.

An interesting point is the following: as seen, $\Delta\vartheta$ is proportional to the optical wavelength and so inversely proportional to the frequency. In the case of *optically wide-band signals* a similar beam squint can occur as in the phased array itself. This may result in a linear distortion of the microwave signal (if the output optical spot is not larger than the aperture of the fiber) or at least in increased coupling between adjacent beams.

An integrated optical delay line-switch architecture is described in [27]. The structure contains four cascaded bidirectional 4×4 switching matrices and 3×4 optical fiber delay lines of different delay (3×0 plus τ, 2τ, 3τ, 4τ, 8τ, 12τ, 16τ, 32τ, and 48τ), for 30 ns maximum delay and $\tau = 470$ ps. The switches of the matrix were of directional coupler construction realized in Lithium-Niobate. Optical insertion loss of various delay values were somewhat higher than in [8] and remarkably uniform, with 13.6 dB minimum loss and 16.7 dB maximum loss. Crosstalk was less uniform, with an average of about 24 dB and a minimum of 14 dB.

It should be mentioned that due to the optical loss incurred in optical switching, *digital delay lines* made up of fibers of lengths increasing by factors of 2 appear to be impractical. Instead, lines of multiples of a given τ are applied—e.g. 128

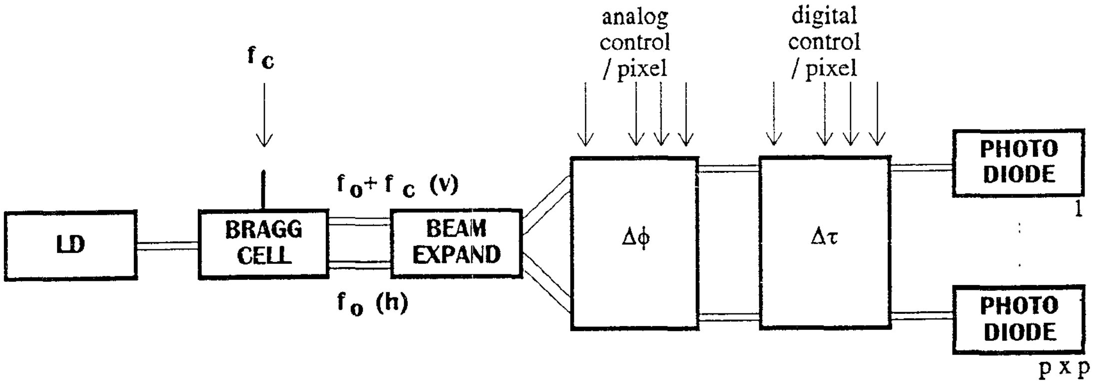

Fig. 3. System design of a heterodyne two-dimensional true-time delay-phase shifting network.

lines of delay T $= 0, \tau, 2\tau, 3\tau, \ldots 127\tau$, rather than 7 lines of T $= \tau, 2\tau, \ldots 64\tau$, with τ the elementary delay.

B. Switching of Free-Space Sections of Variable Length [15], [16], [17]

In principle there is no essential difference between switching of delay lines and of free space sections. The above papers, however, describe methods by which digital delay lines may be realized. Also, both describe *pixelled* structures in which most of the functions are realized via space-division-multiplexing, using the same elements. They are thus two-dimensional structures, realizing an optical image of the phase array on an array of photodetectors.

Reference [15] describes a two-dimensional *coherent* (heterodyned) system. The basic architecture is shown in Fig. 3: a modulated laser beam is produced by a Bragg-cell frequency shifter; the output of this contains the original (f_o) frequency component in one polarization and the shifted ($f_o + f_c$) frequency component in the orthogonal polarization. After optical processing, (i.e. phase and/or time shifting) these are heterodyned on the photodetector array. Pixels of this array produce the image of the antenna array. Time and phase shifters are space-division multiplexed into $p \times p$ pixels, each of which can be addressed electrically. The analog phase shifter is a birefringent liquid crystal, producing its ordinary refractive index for one polarization and a voltage-controllable refractive index for the orthogonal one. The phase difference between the two light waves-and consequently phase shift of the detected microwave signal-can thus be varied by electrical means.

The principle of the digital time delay network is explained next (Fig. 3). It contains a polarization recombiner and N cascaded free-space delay sections producing delays of binary increasing magnitude ($\tau, 2\tau, \ldots N\tau$). One possible design of this delay line is shown in Fig. 4: each pixel of the Spatial Light Modulator (SLM) causes 0 or $\pi/2$ rotation in polarization of the relevant two waves according to the voltage applied; the Polarizing Beam Splitter (PBS) is transparent or total-reflective according to the polarization, forwarding the wave directly to the output or toward the prism P and causing thus 0 or $j\,\tau$ delay, with j a power of 2. The total time-delay-network contains n delay lines as shown in Fig. 4, having identical prisms and PBS-s with different path lengths; and the total optical path-length corresponds to x as given in (14).

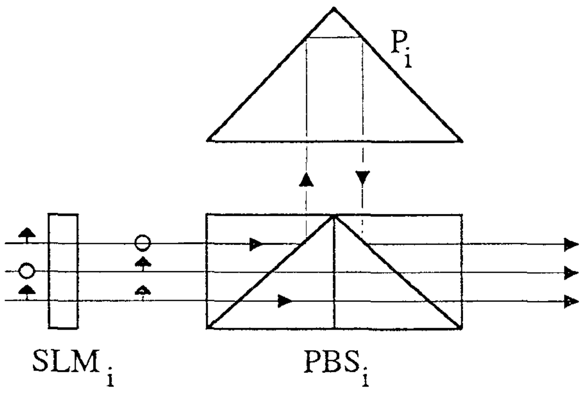

Fig. 4. Delay element of the true-time delay network of Fig. 4.

Reference [15] gives also experimental results, at a frequency of 1.8 GHz, in a simplified architecture. Transmit arrays only are discussed.

A noncoherent, transmit-receive array is described in [17] and shown in Fig. 5. The structure is similar to the preceding one, the main differences being 1) microwave modulation is introduced by intensity modulation (direct or external) of the laser diode rather than by heterodyning, and 2) receive signals are processed by virtually the same optical setup as the transmit signals, with receiver operation requiring one detector rather than a detector array, but an array of (optical) transmitters, rather than a single transmitter. To make the latter operation possible, an array of lasers modulated by the received signal of the antenna elements is provided and an additional Spatial Light Modulator (SLM-R) as well as a Polarization Beam Splitter (PBS), which serves as an optical T/R (Transmit/Receive) switch.

C. True-Time Delay Via Path-Length Dispersion

In [18] an optical delay structure is described the operation of which is based on the principle described at the end of Section III. As shown there, physical lengths of optical paths can be decreased considerably in a heterodyne system, when the path length is dispersed, i.e., made frequency dependent. The key element of this design is a Deformable Mirror Device (DMD) introduced in [19]. This is a semiconductor device comprising a large number of mirrors (typically in excess of 10^5), which can be displaced mechanically via appropriate

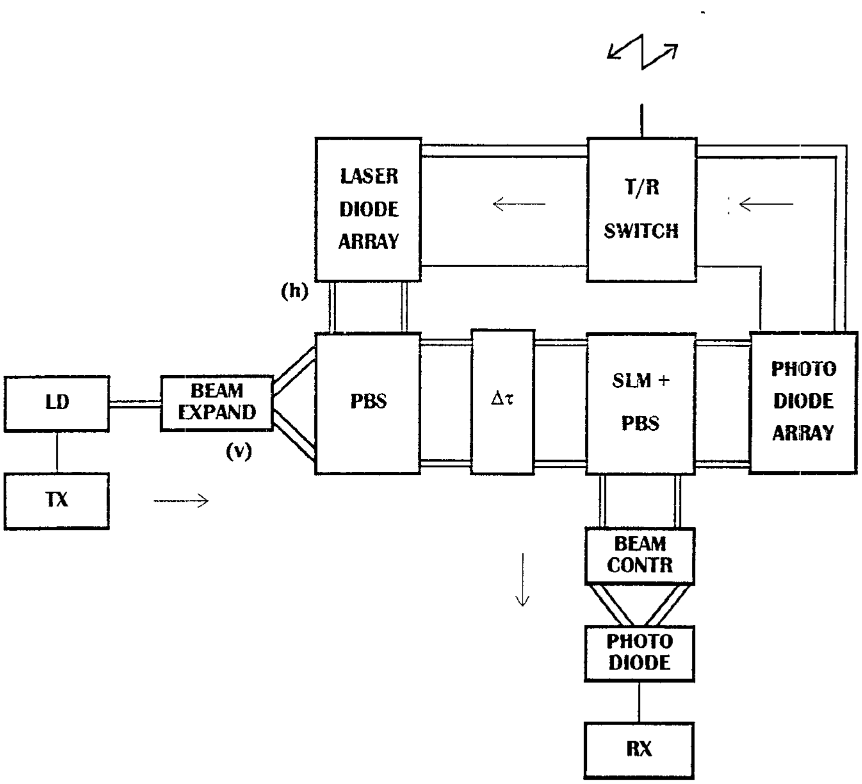

Fig. 5. A nonheterodyning duplex version of the true-time delay network of Fig. 3.

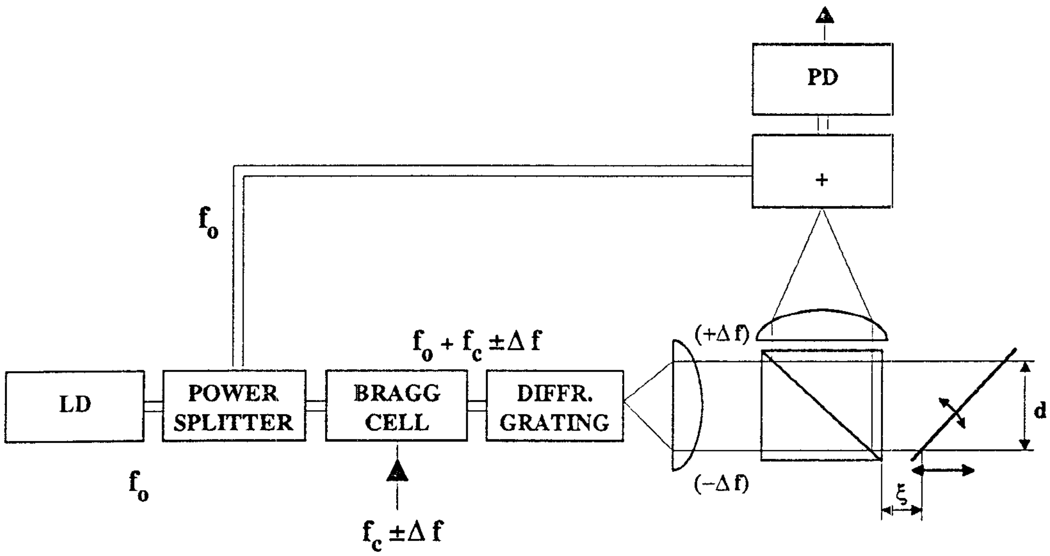

Fig. 6. True-time delay network using a pixelled (mechanically) Deformable Mirror Device (DMD).

voltages and addressed separately. A single delay-system is shown in Fig. 6.

Shifting of the laser frequency is done by the same method as in Fig. 3. One beam containing the microwave signal is forwarded to a diffraction grating causing a *spatial imaging* of the frequency spectrum. The spatially dispersed beam is reflected by the mirror. The mirror is assumed to be movable both in position (translation) and in direction (rotation). By appropriate shifting of the mirror, ξ of (20) can be adjusted and by the appropriate rotation, $\Delta\xi$ of (21) can be adjusted as well. The time-delayed signal is then heterodyned with the other one, yielding the microwave signal of appropriate time delay.

Although this principle seems to be extremely advantageous, a few questions remain still to be answered. Taking into account the extremely low fractional bandwidth in the optical band it is very doubtful that a diffraction grating resulting in the appropriate angular dispersion could be realized. (On the other hand a grating is not the only possibility for achieving this dispersion, as dealt with briefly in [28]; e.g. an acoustooptic device or a microwave filter bank could also be applied.) Further, a somewhat more detailed analysis [29]

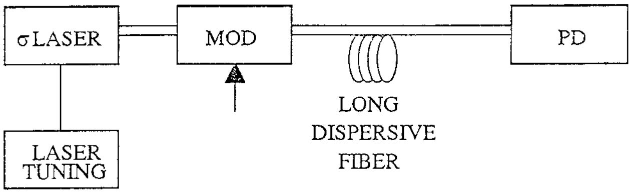

Fig. 7. True-time delay network using a highly dispersive fiber and a tunable laser.

of the structure as given in Fig. 6 shows that a group-delay distortion of the signal will result, mainly due to the presence of the lens.

Reference [18] contains experimental results on an individual delay network. In the experiments 630-nm wavelength light, 70-MHz RF signal and 25-MHz bandwidth were used. However, the grating was replaced by an acoustooptic device and cw signals rather than pulses were only applied; phase shift rather than group-delay was measured. With these restrictions the results have shown good agreement with theory. (It is also to be mentioned that simulation results, described in [28], also show an appropriate operation in the pulsed case.)

D. Optical Line Stretching Via Piezoelectric Effect

A variable delay line of a very simple principle is described in [20] and phased array performance for this design analyzed in [21]. The delay network consists of optical fibers wrapped on a piezoelectric crystal cylinder. As the diameter of this cylinder depends on the electric voltage applied, its circumference can be varied by voltage variation. Thus by increasing the piezoelectric core diameter the length, and so the delay, of the fiber will be increased. Further, by applying several fibers of n, $2n$, $3n\ldots$ windings on one core, the key element, i.e. the piezoelectric cylinder, can be shared among a multiple of radiating elements, e.g. a 16-element array can be designed by using a 4-element crystal bank.

E. Highly Dispersive Optical Guides

The application of waveguide dispersion of an optical fiber is proposed in [22]. The key element of this design is an optical source of extremely wide tuning range. The authors of [22] propose the so-called σ-laser for this purpose [23], which is a relatively complex structure containing a tunable Fabry-Perot interferometer, an erbium-doped amplifier, an optical isolator, and polarization-maintaining fibers and couplers. The design of the time-delay network is shown in Fig. 7.

Measured results use an optical wavelength change of 50 nm (1530–1580 nm) to achieve a change in delay of 1.8 nsec. Note that normal communication quality fiber was used in the experiments; a special, highly dispersive fiber would require a smaller optical tuning range or would give greater change in delay. Such fibers are described in [23]. An operating limit of some 12.5 nsec for 10 GHz carrier frequency is mentioned, above which the delay of the system is no longer frequency-independent; this is of the order of the delays needed in large arrays.

V. DISCUSSION AND CONCLUSION

From the work described above it an be seen that the use of appropriate optical techniques allows true-time-delay phased arrays (or timed arrays) to come closer to practical realization. Although a certain degree of maturity has been achieved in optical principles, only one complete practical realization has been reported thus far [9]. This fact makes a comparative discussion premature. Some comments, however, can be made. The comments to be made refer mostly to *large* arrays processing *wideband* signals, as the first point is the most important to justify the application of optical techniques and the second to apply timed rather than phased arrays.

Although several more elegant solutions were proposed, it seems that the most plausible realization, i.e. that of applying a bank of optical lines and choosing the appropriate one via a switch is the most reliable. Among different realizations of this principle, those applying optical rather than electrical switches are more favorable as only one optical source is needed in this case while in the other one each fiber needs a laser. As a numerical example, in a phased-array-antenna of 10 000 elements with accuracy of 7 bits, the number of light sources would be *1.28 million* lasers. (Of course, using sub-arrays of say 100 elements would decrease this number by 100, but the requirement is still demanding.)

One of the main factors in the choice of an optical switch can be the optical loss; typical practical values to be achieved with present day technology can be as high as 7 dB or so [30]. The acoustooptical switch described in [8] is rather favorable from this point of view. On the other hand, an essentially low modulation index has to be applied there, requiring rather high optical power. Also, the mechanical feasibility of the appropriate matching of say 8 fibers to the acoustooptical device has to be investigated.

Heterodyne systems may have in principle several advantages, including their essential linearity, some particular properties such as spatial dispersion, the resulting decrease of operational lengths, and, in the case of millimeter-wave systems, the possibility of separating the task of very high electrical frequency operation and optical modulation. There are two practical problems: 1) present day technology requires complex optical phase lock loop technology to shift optical frequencies by say 100–200 GHz; and 2) as in most cases, the beams pass through different paths, fiber phase noise influences the spectral purity of the microwave signal generated through heterodyning. Nevertheless, early experimental work [31] indicates that these difficulties can be overcome.

The problem of mechanical stability in free-space delay lines is of great concern and is not investigated thoroughly in the papers referenced. As a numerical example again related to designs described in Section IV-B, the maximum line length needed is given in (14). According to this, the maximum of length x in a free-space design is 0.87 L, i.e. 43 λ in a $\lambda/2$ spaced 100 × 100 element array. The maximum length 1 of Fig. 5 has to be about 22 λ, i.e. 2.2 m at $f_c = 3$ GHz, 67 cm at 10 GHz, and 10 cm at 67 GHz; of these, only the last value seems to be feasible. From this point of view, sub-array constructions are scarcely more favorable.

Length-constraints seem to be much easier in the dispersive path-length design as described in Section IV-C, assuming that the difficulties mentioned there will be resolvable. The maximum of the frequency-dependent optical path-length $\Delta\xi$, as given in (20) and (21) has to be $L\,\Delta\omega/\omega_o \sin\vartheta_0$. On the other hand, based on the geometry given in Fig. 6

$$\Delta\xi = d\tan 2\alpha \approx 2d\,\alpha$$

which approximation is valid as long as the angle of rotation α is small. Again if $l = 20$ m, optical frequency is 500 THz and frequency range is say $\Delta f = 1$ GHz, $\Delta\xi = 34$ μm; if, further, α should not exceed say 4 mrad, the length of the rotable mirrors has to be 4 mm, again a value which seem not to be feasible in a 100 × 100 pixel design. The situation is, of course easier, if array dimension and/or bandwidth are decreased. For example by decreasing the bandwidth to say 25 MHz (the band of the experiments of [18]), and the aperture length to 5 m, mirror length can be decreased by a factor of 160; .025-mm mirror length could be realizable.

Perhaps the most elegant solution of the true-time-delay problem would be that using waveguide dispersion, as both the application of switches and of mechanical movement are excluded. The complexity, however, of the system proposed in [22], particularly that of the tunable σ-laser, should be reduced in order to find widespread practical application. The piezoelectric line-stretching would require high operating voltages and would have restricted operating speed.

To conclude, several variable optical time delay systems have been described based on different principles. Further experiments, and in particular experiments made on phased arrays, are needed to show the *pros* and *cons* of the various principles. Some numerical examples have shown that the described principles, although not applicable for extremely large *and* extremely wideband applications, can well fulfill moderate requirements in phased array systems.

VI. APPENDIX

The group delay to be realized, i.e. the derivative of the phase shift, can be given as

$$\frac{d\psi}{d\omega} = \frac{y\sin\vartheta_0}{c}.$$

If realized in the optical band, a line of length ξ has to be applied. The phase shift of the line and its slope are

$$\psi = \frac{(\omega_o + \Delta\omega)\,\xi}{v};\ \frac{d\psi}{d\omega} = \frac{\xi}{v} + \frac{\omega}{v}\frac{d\xi}{d\omega}.$$

Case 1: The line length is constant. Then the slope can only be achieved if $\xi = x = y\sin\vartheta_0 v/c$

Case 2: If, however, ξ is a function of frequency, then a much shorter ξ is sufficient. From the above equation

$$\frac{d\xi}{d\omega} = \frac{y\,\frac{v}{c}\sin\vartheta_0 - \xi}{\omega_o}.$$

To obtain the apprppriate phase shift at the nominal (optical) carrier we need a length

$$\xi = y\sin\vartheta_0\,\frac{v}{c}\,\frac{\omega_c}{\omega_o}$$

and thus

$$\frac{d\xi}{d\omega} = \frac{y\sin\vartheta_0\,\frac{v}{c}\left(1 - \frac{\omega_c}{\omega_o}\right)}{\omega_o} = \left(1 - \frac{\omega_c}{\omega_o}\right)\frac{\xi}{\omega_c}$$

or

$$\Delta\xi = \left(1 - \frac{\omega_c}{\omega_o}\right)\frac{\Delta\omega}{\omega_c}\,\xi.$$

Further, to show that the group delay as adjusted above solved really the problem of bandwidth in phase arrays take into account (9), according to which phase shift has to be proportional to the frequency. Write e.g.

$$\psi = \psi_L\,\frac{\omega}{\omega_L}$$

with ω_L the lowest frequency and ψ_L the phase at that frequency.

Let the lower edge of the mirror be at a distance ξ from the cube, the length of the mirror be d, and the mirror inclination α (see Fig. 6). Then, the optical path of a component of (optical) angular frequency ω_o is

$$l(\omega_o) = 2\xi + d\tan 2\sigma\,\frac{\omega_o - \omega_{oL}}{\omega_{oU} - \omega_{oL}}$$

where subscript U stands for the upper frequency limit and o for frequencies in the optical band. The corresponding phase shift in the optical domain is

$$\psi(\omega_o) = l(\omega_o)\,\frac{\omega_o}{c}.$$

Of course, after heterodyning this phase shift is transferred to the microwave band. Due to the requirement of (9), we need at the upper frequency a phase shift $\psi_U = \psi_L\,\omega_U/\omega_L$. We have thus

$$\psi_U = 2\xi\,\frac{\omega_{oU}}{c} + d\tan 2\alpha\frac{\omega_{oU}}{c} = 2\xi\,\frac{\omega_{oL}}{c}\,\frac{\omega_U}{\omega_L}$$

leading to

$$d\tan 2\alpha = 2\xi\left(\frac{\omega_{oL}}{\omega_{oU}}\,\frac{\omega_U}{\omega_L} - 1\right).$$

Thus, if both ξ and $d\tan\ 2\alpha$ are chosen in accordance with the above, the optical phase shift and also the microwave phase shift will be proportional to the (microwave) frequency—required to counteract beam squinting.

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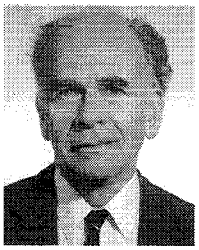

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