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Voltage-controlled optical/RF phase shifter — Source link

Richard A. Soref

Institutions: Hanscom Air Force Base

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Voltage-Controlled Optical/RF Phase Shifter

RICHARD A. SOREF, SENIOR MEMBER, IEEE

Abstract—**A new fiber-optic device designed to steer the radiation beam of a phased-array antenna has been demonstrated. A radiofrequency (RF) signal at 125 MHz is generated via photomixing at the output of a single-mode fiber-optic interferometer. The phase of the electrical signal is shifted over several cycles in direct proportion to a voltage applied to an optical controller. The controller consists of a Pockels-type optical phase modulator located in one arm of the heterodyne interferometer. Rapid changes in RF phase are feasible. A miniature low-voltage version of the device, based upon integrated optics, is proposed.**

I. Introduction

THIS PAPER describes a novel voltage-controlled RF/microwave phase shifter intended for phased-array antenna applications. An RF electrical signal is generated by square-law mixing of optical signals from a heterodyne interferometer, and the radiofrequency (RF) phase is shifted in proportion to a voltage applied to a Pockels-type optical phase modulator. The modulator is located in one arm of the interferometer. It may appear difficult to obtain adequate RF phase shift with an optical perturbation because the RF wavelength is $\sim 10^6$ longer than the optical wavelength. Nevertheless, as shown here, 2π rad of optical phase modulation will produce an immediate shift of 2π rad in the electrical phase angle.

The heterodyne concept is discussed below, and experimental results on two interferometers, free-space and fiber-optic, are presented. An implementation of the device on an integrated optical chip is also proposed. Because the phase shifter can be built on a 1×2 cm chip, monolithic integration of several low-voltage shifters on one chip is feasible. Some details of the proposed antenna application are also given.

II. Theory

An optical Mach–Zehnder heterodyne interferometer contains an optical frequency translator to upshift or downshift the initial light frequency. The frequency offset can be in the RF range, for example. If the interferometer output is fed to a square-law detector (any conventional photodiode), an RF beat note will be observed. Now, if an electrooptical phase shifter is inserted into either arm of the interferometer, it will be possible to control the phase of the electrical beat note by controlling the optical phase. This property has not been generally appreciated.

Fig. 1 illustrates how the electrical signal is produced by coherent mixing of two light signals. At the interferometer input, the CW light beam from the coherent source is divided into equal signals of the form $(A_o/\sqrt{2}) \cos \omega_o t$, where ω_o is the optical frequency and A_o is the optical source amplitude. In the first arm, a single-sideband optical frequency shifter operating at the radio frequency ω_r modifies the first optical signal into $(A_o/\sqrt{2}) \cos (\omega_o + \omega_r)t$. In the second arm, a voltage-controlled optical phase shifter retards the optical phase by an amount $\phi_2(V_2)$, which changes the second optical signal into $(A_o/\sqrt{2}) \cos (\omega_o t + \phi_2(V_2))$. (For the time being, we shall assume that $\phi_2(V_2)$ is not time varying.) At the interferometer output, the total optical electric field E_t is $(A_o/\sqrt{2})$ $[\cos (\omega_o t + \omega_r t) + \cos (\omega_o t + \phi_2(V))]$. The detector response is proportional to the time average of $|E_t|^2$ over an optical cycle. Therefore, the observed photovoltage is

$$v_{\text{out}} = \text{const} \times (A_o^2/2) \, [1 + \cos (\omega_r t - \phi_2(V_2))] \quad (1)$$

a signal that consists of a dc term and an RF term. Let us consider only the ω_r term in (1), as in an ac-coupled detector. If a voltage step V_2 is applied to the optical shifter so as to produce a specific amount of optical phase retardation (several cycles, for example), then the RF electrical phase is shifted by the same amount. This is the principal result here.

Regarding the optical polarization states within the interferometer, we can decompose the light in each arm into orthogonal polarization components labeled s_1, p_1 and s_2, p_2. (The reference plane for s and p is determined by the frequency shifter). At the interferometer output, we note that s_1 mixes with s_2, and that p_1 mixes with p_2. However, s_1 does not interfere with p_2, nor does p_1 interfere with s_2. In the Fig. 1 Mach–Zehnder arrangement, it is assumed that the optical path lengths of the two arms are nearly the same, and that the path difference is less than the coherence length of the optical source.

Having described the phase shifter in its simplest terms, we wish now to examine a more general shifter. First, we introduce fiber-optic transmission lines to carry light from the source to the interferometer and from the interferometer to the photodiode. Second, an additional electrooptic phase modulator $\phi_1(V_1)$ is inserted in series with the Δf element for "phase trimming." Third, we now recognize that there are initial phase angles associated with the optical source (ϕ_s) and with the optical frequency shifter (ϕ_r). Fourth, we note that the frequency translation process is characterized by an efficiency factor η. (Implicit in η is an RF drive level).

Fig. 2 illustrates the general case. The propagation con-

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The author is with Rome Air Development Center, RADC/ESO, Hanscom, AFB, MA 01731.

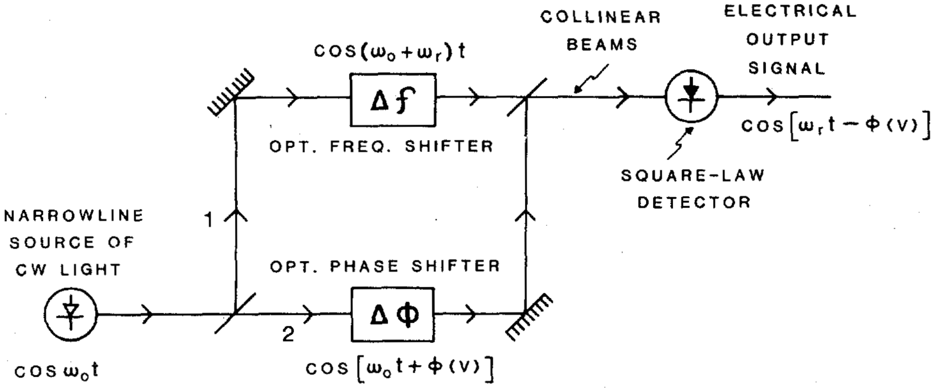

Fig. 1. Mach–Zehnder $\Delta\phi$ and Δf technique for controlling the phase of a difference-frequency electrical signal.

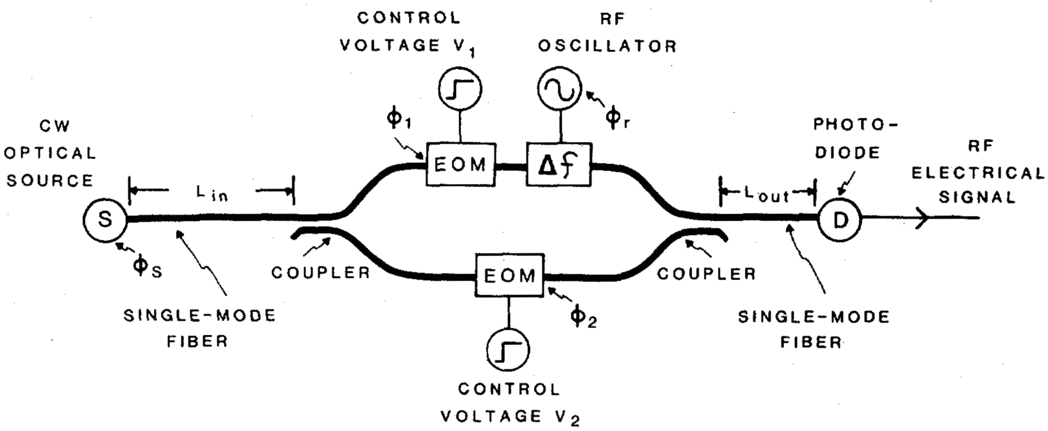

Fig. 2. Generalized guided-wave heterodyne intereferometer.

stants of the fiber-optic transmission lines are β_o at the frequency ω_o and β_{or} at the frequency $\omega_o + \omega_r$. The fiber line lengths are L_{in} and L_{out}, respectively. Note that the phase angle ϕ_r of the RF oscillator driving the frequency shifter is transferred directly from the electrical domain to the optical domain. This follows from the nature of the physical interaction. For example, if the frequency-shifting is done acoustooptically, it can be shown that there is a one-to-one correspondence between the phase angle of the traveling acoustic wave and the phase angle of the diffracted optical wave. There are static optical phases ψ_1 and ψ_2 associated with the first and second paths in the interferometer. This occurs because one path may be slightly longer than the other, and because there is a 90° relative phase shift between the two optical signals that emerge from an optical directional coupler. (The 90° shift applies to both couplers in Fig. 2.)

Proceeding with the analysis of Fig. 2, we note that the two optical waves entering the interferometer are both of the form $\cos(\omega_o t + \phi_s + \beta_o L_{\text{in}})$ with amplitude $A_o/\sqrt{2}$. After traversing the interferometer, the two signals are $(\eta A_o/\sqrt{2}) \cos(\omega_o t + \phi_s + \beta_o L_{\text{in}} + \omega_r t + \phi_r + \psi_1 + \phi_1(V_1))$ and $(A_o/\sqrt{2}) \cos(\omega_o t + \phi_s + \beta_o L_{\text{in}} + \psi_2 + \phi_2(V_2))$, respectively. Each lightwave picks up an additional phase, either $\beta_o L_{\text{out}}$ or $\beta_{or} L_{\text{out}}$, as it travels to the photodiode. Thus, at the detector, the combined optical E-field is

$$E_t = (\eta A_o/\sqrt{2}) \cos \Phi_1 + (A_o/\sqrt{2}) \cos \Phi_2$$

where

$$\Phi_1 = (\omega_o + \omega_r)t + \phi_s + \beta_o L_{\text{in}} + \phi_r + \psi_1 + \phi_1(V_1) + \beta_{or} L_{\text{out}} \quad (2)$$

and

$$\Phi_2 = \omega_o t + \phi_s + \beta_o L_{\text{in}} + \psi_2 + \phi_2(V_2) + \beta_o L_{\text{out}}.$$

The calculation of $\langle |E_t|^2 \rangle$ then gives the following result for the detector signal:

$$v_{\text{out}} = \text{const} \times (A_o^2/4)\,[\eta^2 + 1 + 2\eta \cos(\Phi_1 - \Phi_2)]. \quad (3)$$

Only the difference frequency term $\cos(\Phi_1 - \Phi_2)$ is found in the ac-coupled output, and in the $\Phi_1 - \Phi_2$ phase difference, the phase components $\beta_o L_{\text{in}}$ and ϕs are subtracted out. Thus, we obtain from (2) and (3) the RF result:

$$v_{\text{out}} = \text{const} \times (\eta A_o^2/2) \cos[\omega_r t + \phi_r + \phi_1(V_1) - \phi_2(V_2) + \Delta\psi + \Delta\beta L_{\text{out}}] \quad (4)$$

where $\Delta\psi = \psi_1 - \psi_2$ and $\Delta\beta = \beta_{or} - \beta_o$. Now, the RF phase is controlled by the phase differnce between the optical controllers $\phi_1 - \phi_2$ and by ϕ_r. The ϕ_1 controller affords an extra degree of freedom because it can be used to synchronize several shifters. For example, if L_{out} differs from a standard length, then ϕ_1 can compensate for this

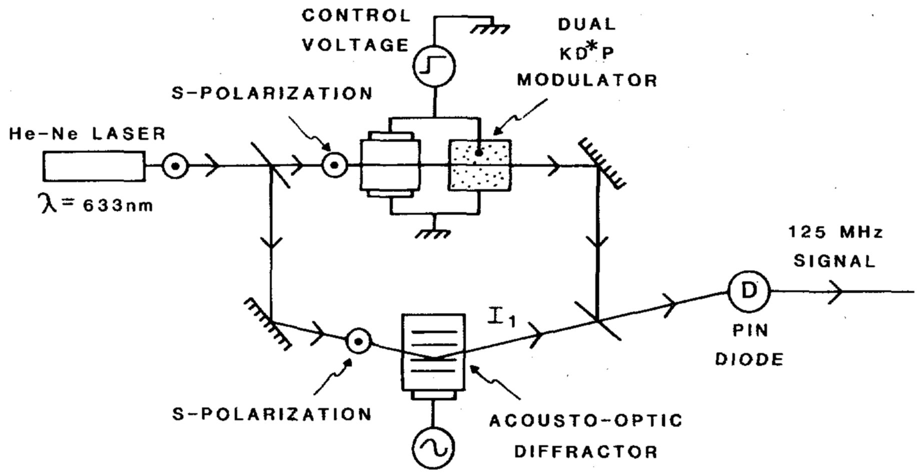

Fig. 3. Experimental free-space setup.

deviation and can "initialize" a given shifter. More generally, the trimmer would be set to compensate for both phase errors: $\phi_1(V_1) + \Delta\psi + \Delta\beta L_{out} = 0$. Also, for Pockels-type controllers, $\phi_2 = kV_2$ and the RF output phase will be linear in voltage. Amplitude control of the RF output signal is available by controlling the optical source amplitude, or the RF input level, or the conversion efficiency, or a combination thereof. The above theory predicts that the RF output phase will be invariant with respect to the input transmission-line length and to the optical source phase.

Thus far, V_1 and V_2 have been assumed to be steady (dc) potentials, but a time-dependence is implicit in V_1 and V_2. Fast switching of the RF phase angle can be attained with a rapid stepwise transition from one level to another (e.g., V_2 to V_2) which represents "digital" control. Or, a continuous "analog" change in phase is feasible. It is relatively easy to control the voltage levels V_1 and V_2 accurately. Therefore, one can, in principle, obtain high accuracy RF/microwave phase control, and the accuracy may be better than that offered by conventional microwave phase control methods.

III. Experiment

Fig. 3 shows the free-space interferometer used in our first experiment. Two mirrors and two 50/50 beamsplitters were used. The linearly polarized He–Ne laser beam (λ = 633 nm) had a diameter of about 1.2 mm and a 2 mW CW power level. This collimated beam was polarized at 90° to the plane of incidence of an acoustooptic frequency shifter (s-polarization) for optimal diffraction. (The diffraction is negligible for the p-component). About 75 percent of the first beam was Bragg-diffracted into the first order (I_1 in Fig. 3) producing a single sideband shift of 125 MHz in the light frequency. The electrooptic modulator (Lasermetrics model 3078) contained two KD*P crystals in optical cascade. The crystals had a 90° relative rotation to cancel the static birefringence of the combination. The electrodes on each crystal applied a field transverse to the optical propagation. The s-polarized light in arm #2 was oriented along the x' axis of the first KD*P crystal, but was polarized along z in the second crystal; thus only the first crystal was active in producing an electrooptic phase shift. (Both crystals contribute to retardation in the traditional 45°-polarization experiment used to measure the halfwave voltage V_p). Thus, for this transverse Pockels-effect-modulator, the voltage-induced phase retardation is: $\phi_2(V_2) = (\pi/2)(V_2/V_p)$ rather than the usual $\pi V_2/V_p$ expression [1]. In a separate experiment, we measured V_p = 260 V dc at 633 nm.

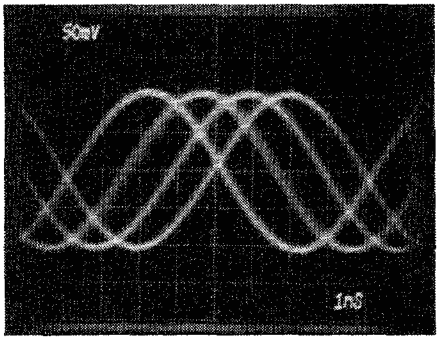

Fig. 4. Shift of RF beat note during electrooptical control.

After being superimposed at the second beamsplitter, the two light beams were incident on the 5-mm^2 sensing area of an Si p-i-n photodiode that had a 1.7-ns rise time. Care was taken to make the beams sufficiently collinear so that the interference fringe width was greater than the detector width. The RF beat note was amplified 40 dB and displayed in real time on an oscilloscope. A fixed RF phase-reference was obtained by triggering the scope externally with the RF voltage used to actuate the AO cell. The multimode laser, which had a resonant cavity length of 24 cm, produced several cavity-mode beat notes, but those notes were all at frequencies higher than the 150-MHz amplifier passband and were not observed. The voltage level of the dc supply actuating the EO cell was stepped up and down in 150-V dc increments. Fig. 4 shows the time dependence of the 125-MHz electrical output when voltages of zero, 150, 300, and 450 V dc were applied to the EO cell.

The voltage applied to the optical controller was in-

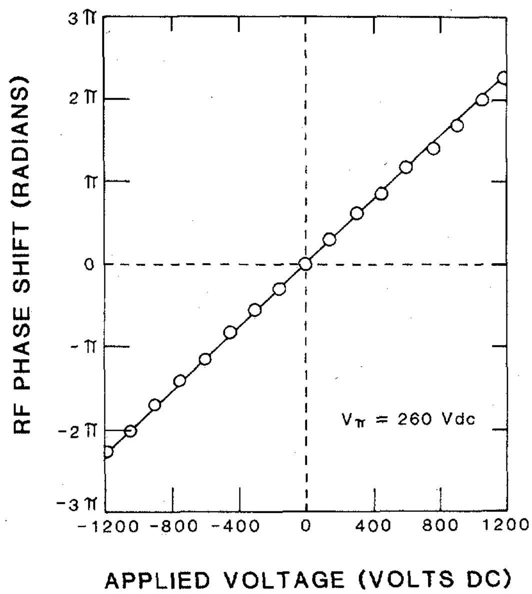

Fig. 5. Electrical output phase versus control voltage..

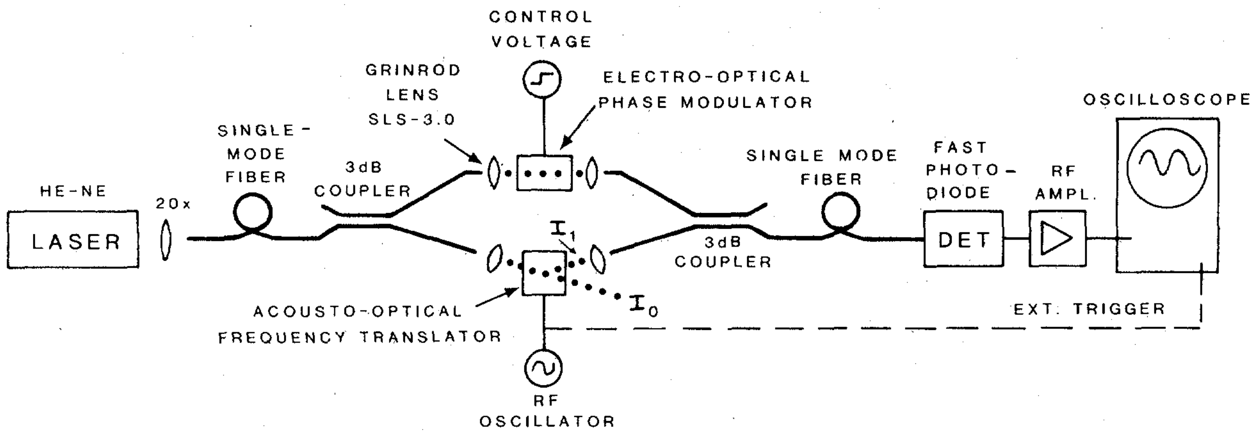

Fig. 6. Experimental arrangement utilizing single-mode fiber.

creased from -1200 V dc to $+1200$ V dc and the resulting 125-MHz electrical phase shift was plotted versus V_2 in Fig. 5. This result demonstrates multicycle control, polarity independence, and linearity as predicted by theory. We found that one cycle of shift (2π rad) occurred when $V_2 = 4V_p$ as predicted above. This verified the expected 1-to-1 correlation of optical phase with electrical phase. The EO cell was moved from arm #2 to arm #1 with similar results. To check the effects of acoutic phase, we inserted various lengths of coaxial cable in series with the AO driver and qualitatively verified the ϕ_r dependence predicted in (4).

Guided-wave optics were used to the next experiment, and a single-mode fiber-optic interferometer was set up (Fig. 6). However, since the AO and EO cells are bulk-optic devices, it was necessary to interrupt the fiber at two locations to insert these cells. At each location, a pair of 3-mm-diam grinrod lenses (SLS-3.0–0.25p) served to collimate light from the first fiber for passage through the cell, and to refocus that light onto the core of the second fiber. This required a 13-cm lens-to-lens separation in air for the EO cell, and a 9-cm separation for the AO cell. In the AO case, the second grinrod captured only the first-order diffracted beam. The second grinrods were mounted on 5-axis micropositioners.

The interferometer was made from two fused biconical-taper couplers, nominally single-mode 3-dB directional couplers made from Corning 66202 fiber.[1] The 70-μm OD fibers had a core diameter of 4.5 μm. They had a single-mode cutoff at 732 nm and could support two modes at 633 nm. However, we excited only the fundamental mode with laser light focused on-axis by a 20× objective. The interferometer arms were 2 m long, with 1-m input and output leads.

In Fig. 6, the 125-MHz beat note was weaker than that in Fig. 3 for two reasons. First only the polarization component normal to the AO plane is active in photomixing, which introduces 3 dB of optical-to-RF conversion loss relative to Fig. 3. Second, although the fibers were not nominally polarization preserving, they did tend to maintain the input polarization over short lengths and the re-

[1]These couplers were kindly supplied to us by D. C. Johnson of the Government of Canada [2].

sulting elliptical polarization states were randomly oriented.

In Fig. 6, the measured voltage-induced RF phase shift was identical to that in Fig. 5. However, the measurement accuracy was hampered by a slow, random drift in the initial ($V_2 = 0$) RF phase. We attribute the drift to temperature-fluctuation effects in the fiber arms, to air convection between the lenses, and to microscopic motion of the lens holders. The drift was diminished by enclosing the interferometer in a box. Measurements of phase noise were not made in these initial studies. Phase drift is not expected to be a problem in the integrated-optic structure discussed in Section V below.

Two final experimental notes: the input fiber was cleaved to various lengths without affecting the RF output phase, and an EO modulator at the input confirmed the invariance of output phase with respect to ϕ_s.

IV. The Antenna Application

Present-day phased array antennas are controlled by microwave phase shifters that are fairly lossy, bulky, and expensive. In the future versions of the antenna, it is hoped that the conventional shifters will be replaced by smaller lower-power devices (such as optical devices) and that most of the bulky microwave waveguides will be eliminated. The "optical/microwave" antenna is an intriguing new kind of phased-array antenna that uses fiber-optic transmission lines in the antenna feed [3], [4] in lieu of microwave guides. This "hybrid" antenna offers the prospect of improved control by transferring control to the optical domain.

A number of optical/microwave structures have been proposed [5]–[7], and there is still debate about the best antenna architecture, but it is likely that $N \times M$ fiber lines will connect a digital electronic computer (array processor) to a set of $N \times M$ electronic solid-state modules. There would be one module for each of the $N \times M$ radiant elements in the array, and each module would contain a microwave amplifier. In this scenario, the radiation beam of the transmitting antenna could be formed using a set of electrooptical phase shifters. The antenna would include $N \times M$ fiber-coupled devices of the type described in Section V below, and the microwave energy would be generated at low power levels by photomixing. Then, the phase-related microwave signals would be amplified and radiated. The modular optical/microwave antenna could operate also in a receive mode, which would require a "direction finding computer," a second set of $N \times M$ amplifiers, and another set of $N \times M$ optical/RF phase shifters.

Rapid electronic beamsteering is an important goal for the phased-array antenna of the future. Time-delay beamsteering and phase-shift beamsteering are the two main approaches [8]. Optical time-delay beamsteering was discussed briefly in [9], while this paper is concerned with the phase-shifting approach. For antennas with an instantaneous microwave bandwidth of 2 percent or less, phase shift steering will give accurate beampointing.

The phase controllers here are based on the Pockels effect, which is inherently quite fast. In those EO modulators, circuit restrictions on switching speed could be minimized by utilizing a guided-wave structure (Section V) with traveling-wave electrodes. Thus, it should be possible to alter the RF/microwave phase angle in less than 1 ns. Therefore, the present shifters offer the hope of highly agile, electronic beamsteering in an optical/microwave antenna.

V. Integrated Optical Structure

A compact low-voltage embodiment of the phase shifters described in Section III would be required for a practical optical/microwave antenna. Interferometric structures are well known in the integrated-optics art, both for sensors and high-speed modulators, and fiber-coupled integrated optical devices are well established. Therefore, an integrated optical (IO) structure is an excellent candidate for the miniature phase controller. The expected stability of this interferometer and the resulting stability of the RF/microwave beat signal are the main motivations for selecting the IO approach. Temperature variations and other environmental factors have an equal effect on each path in an integrated interferometer because the paths share a common substrate. Hence, a net cancellation or "common mode rejection" of phase-drift factors is expected at the output coupler of the interferometer. Experimental evidence for such stability has already been found.

The proposed IO chip would contain channel waveguides in a Mach–Zehnder layout and would be coupled to single-mode fibers at both input and output. Those fibers could be polarization preserving or not, depending upon the modal properties of the active elements. The fiber cores would be aligned precisely with the IO channels by means of V-grooves formed in a preferentially etched Si substrate. The materials used in the IO circuit could be III-V semiconductor materials or dielectric materials such as single-crystal $LiNbO_3$. In the latter case, Ti-diffused channels can support TE modes, TM modes, or a TE-TM combination.

There are several viable choices for the active elements. It is well known that surface acoustic waves can diffract and upshift light in a slab guide, but we prefer a channelized all-electrooptic approach to frequency shifting.[2] There are three recent examples of channel-type electrooptic frequency shifters in the IO literature: 1) a traveling-wave three-phase TE-to-TM mode converter [11], 2) a four-branch TM-mode structure containing balanced electrooptic modulators [12], and 3) a traveling-wave 2-phase TE-to-TM mode converter that has a comb-like appearance [13]. The electrooptic phase shifter in a $LiNbO_3$ wafer could consist simply of a parallel-pair of electrodes

[2]Very recently, acoustooptical frequency shifting in channel waveguides was announced by C. T. Lee and by R. Th. Kersten [10].

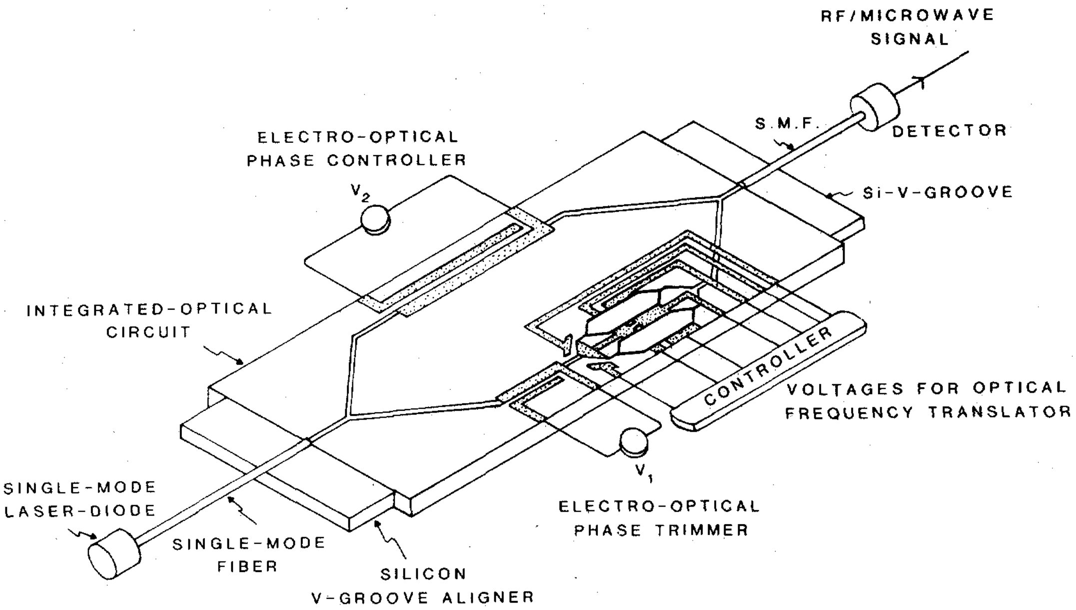

Fig. 7. Proposed integrated-optical embodiment of optical/RF phase shifter.

that straddle a channel-guide so as to modify its propagation velocity with an applied E-field. In the IO devices mentioned here, the maximum operating voltages are approximately 50 V, and 10^9 switching operations per second are feasible.

At the output Y-branch coupler of the IO structure, TE modes interfere only with TE modes, and TM modes only with TM. Because of this design constraint, it is probably simplest to choose an all-TM-mode approach for the IO circuit, rather than to select a design that supports TE and TM. Fig. 7 shows a proposed TM_o-mode integrated optic structure that uses the four-branch frequency shifter of Izutsu *et al.* [12] in z-cut Ti : $LiNbO_3$. (The SSB frequency translator was tested at 2 GHz in [12].) The various control electrodes are shown. To utilize the r_{33} electrooptic coefficient, one electrode of each pair is deployed atop the channel to produce z-components in the applied field.

VI. Summary

An electrooptic technique for controlling the phase and amplitude of an RF/microwave electrical signal has been demonstrated. The technique includes a heterodyne optical interferometer with a Pockels-type optical phase modulator in one path. Accurate, multicycle control of the RF phase angle is afforded by applying an accurate voltage step to the modulator. The controller can change the RF phase angle very rapidly, for example, in a few nanoseconds, and the phase shifting device is fiber coupled for remote transmission of high-frequency signals. With the aid of integrated-optical technology, it is possible to build the phase shifter on a small "chip" coupled at both ends to single mode fibers. In addition to miniaturization, this monolithic optical structure would have a number of advantages over the fiber-optic interferometer described in this paper: lower-voltage control, faster switching, and greater stability with respect to environmental factors that can lead to phase drift. A group of integrated shifters can be used for electronic beamsteering of a phased-array antenna.

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Richard A. Soref (S'58–M'63–SM'71)received the B.S.E.E. and M.S.E.E. degrees from the University of Wisconsin in 1958 and 1959 and the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, in 1963.

From 1963 to 1965, he worked in the optics and infrared group of M.I.T's Lincoln Laboratory, and in 1965, he joined the Technical Staff of Sperry Research Center in Sudbury, MA, where he conducted research on a variety of topics including nonlinear optics, infrared detection, liquid crystal electrooptical devices, optical switching, and fiber-optic sensors. In November 1983, he joined Rome Air Development Center, Hanscom AFB, MA, as a Research Scientist in the Solid State Sciences Division. Integrated optics is his current research interest. He has authored approximately 60 journal articles and holds 14 patents.

Dr. Soref is a member of APS, SPIE, and OSA. He served as Chairman of the Boston Chapter IEEE Group on Electron Devices in 1969. He is currently a member of the Editorial Board of *Optical Engineering.*