Influence of Crosstalk in Switchable Optical Time-Delay Networks for Microwave Array Antennas

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***Abstract*— Switchable optical time-delay (TD) networks are used for the phase control of array antennas and for microwave signal processing because of their wide instantaneous bandwidth. In each optical switch, crosstalk signals are generated and its influence on the microwave phase accuracy is investigated. Due to the crosstalk of the switches, each stage forms an interferometer which converts the phase noise of the optical source into amplitude noise whose influence on the microwave phase is analyzed.**

***Index Terms*— Microwave antennas, microwave communication, optical delay lines, optical signal processing, signal-processing antennas.**

I. Introduction

IT HAS become increasingly apparent that the next generation of electronically scanned array antennas will require smaller and higher performance signal distribution and true time-delay (TTD) beamforming networks. The latter characteristics provide wide instantaneous bandwidth at each steering angle. This eliminates beam squint and enables narrow pulse operation on large antennas [1], [2]. Photonics technology has the potential for having a tremendous impact on the architecture and realization of these systems. Photonic device and circuit technology can implement modulation and TTD beamforming functions on the microwave-modulated lightwave signals and provide much wider bandwidth than was presently possible with monolithic-microwave integrated-circuit (MMIC) technology.

In this paper, a transfer matrix model is used to generate switching networks, i.e., switchable TTD lines consisting of 2×2 optical switches with different specifications and states. In the switching network, the signal-to-crosstalk ratio and, therewith, the phase error of the microwave signal is evaluated. Due to the crosstalk of the switches, each stage forms an interferometer which converts the phase noise of the laser source into amplitude noise at the output. This additional noise reduces the signal-to-noise ratio of the system and, therefore, the phase accuracy of the microwave signal.

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II. Transfer Matrix Model of a TTD Network

A 4-b TTD network is outlined in Fig. 1. Due to imperfect optical switches in every stage, new signals due to crosstalk are generated. At the output of the TTD network we get the desired signal and a summation of crosstalk signals with different amplitudes and phases depending on the way they propagate through the network. To analyze the influence of the increasing number of crosstalk signals on the phase of the output signal, the power transfer matrix model is used [3]. The losses of the switching element are expressed by the power fractions a and b, as outlined in Fig. 2. The crosstalk c represents the fraction of power that is coupled into the other channel. The relation between the input and output power vectors $(\mathbf{P_{in}}, \mathbf{P_{out}})$ is expressed by the matrix $\mathbf{SW}$, where s describes the state of the switching element ($s = 0$: cross state, $s = 1$: bar state) and $d = 1 - a = 1 - b$, shown in (1) at the bottom of the following page. The interconnection between two switching elements is expressed by the matrix $\mathbf{DL}$ as follows:

$$\mathbf{DL} = \begin{bmatrix} (1-a)\cdot \exp(-j\omega\tau) & 0 \\ 0 & (1-b) \end{bmatrix}. \tag{2}$$

The delay time τ is realized with two interconnecting waveguides of different length ΔL. The losses of the waveguides are a and b. These transfer matrix models are used to describe the topology of the network. An n-b TTD network is represented by the multiplication of n matrices $\mathbf{DL_j}$ and $(n+1)$ matrices $\mathbf{SW_j}$. In general, the output power vector $\mathbf{P_{out}}$ is given by $\mathbf{P_{out}} = \mathbf{SW_{n+1}} \cdot \mathbf{DL_n} \cdot \mathbf{SW_n} \cdot \cdots \cdot \mathbf{DL_1} \cdot \mathbf{SW_1} \cdot \mathbf{P_{in}}$. For the sake of simplicity, it is assumed here that the losses $a = b$ and that c is identical for both channels and states. Due to imperfections of the manufacturing process of a TTD network, crosstalk and waveguide length have varying values. Here, crosstalk and length are taken to be independent Gaussian random variables with variances σ_c^2 and σ_L^2, respectively.

A 4-b TTD-device layout is shown in Fig. 1 [4]. For a center frequency of 12.5 GHz ($T = 80$ ps), the required length differences of the waveguides to be built in different material systems are given in Table I.

The system analysis is carried out for crosstalk levels c between $-12, \cdots, -30$ dB. Instead of aligning each switch on lowest crosstalk, we use one switching voltage for all switches and take into account the variance of the crosstalk [4]. As a

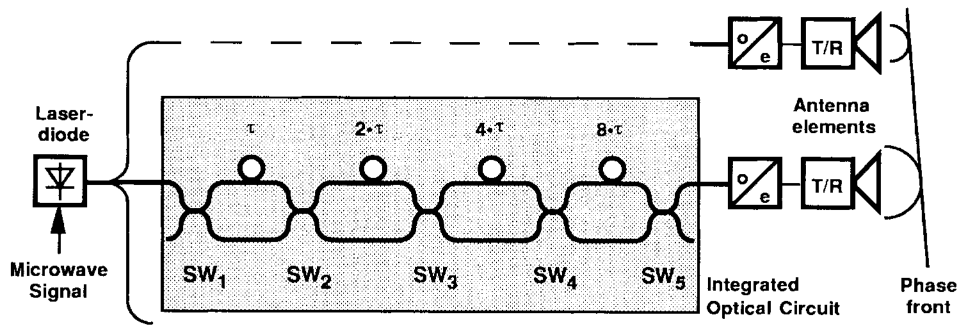

Fig. 1. 4-b TTD network for wide-band signal processing in a phased-array antenna (T/R: transmit/receive-modul, o/e: optical receiver).

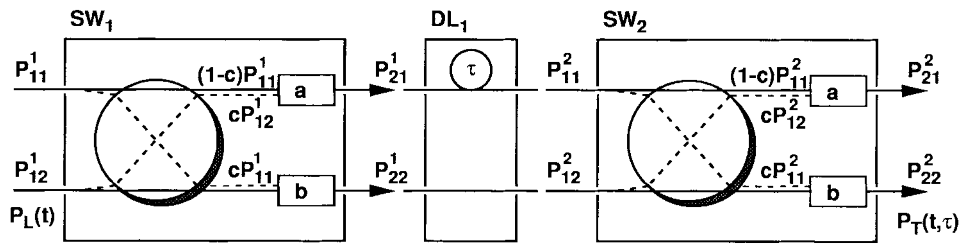

Fig. 2. Transfer matrix model of one stage of the TTD network. Switches are in bar state (a, b: losses, c: crosstalk).

TABLE I
LENGTH DIFFERENCES ΔL_i OF THE OPTICAL WAVEGUIDES FOR TIME DELAYS $\Delta t_i = T/2^i$ AND PROPAGATION SPEED v IN USUAL MATERIAL SYSTEMS ($\Delta t_i = \Delta L_i/v$)

	$LiNbO_3$	Polymere	Si	GaAs
ΔL_1 [mm]	0.67	0.93	0.43	0.42
ΔL_2 [mm]	1.33	1.85	0.86	0.83
ΔL_3 [mm]	2.66	3.70	1.71	1.67
ΔL_4 [mm]	5.33	7.41	3.43	3.34
v [μm/ps]	133	185	85.7	83.3

result of the simulation, the signal phase error of a 4-b TTD network is given by

$$\Delta\varphi = 5^\circ \cdot 10^{\left(1+\frac{c}{13.2\,\mathrm{dB}}\right)}. \tag{3}$$

Two prototypes of 4-b TTD devices were built on Z-cut $LiNbO_3$. One device had a crosstalk per switch of -17 ± 2 dB and a phase error of 3°, the second one a crosstalk of about -22 ± 2 dB and a phase error of 1.2°. The measured phase error of the microwave signal is somewhat higher ($\approx 0.5^\circ$) than the predicted value. The phase error due to the inaccuracy of the length of the delay lines yield an error of $\Delta\varphi = \pm 0.5^\circ$ for $\pm$ 5-μm-length accuracy in our Z-cut $LiNbO_3$ device. If delay times $\tau \gg T$ are needed, the delay lines must be realized with optical fibers because of the limited area on integrated optical circuits. Carefully produced fiber lengths are controlled to be $\pm$ 0.5 to $\pm$ 0.75 mm of their nominal values [4]. This inaccuracy results in a microwave phase error of about $\pm$ 9°, a value which is clearly larger than the error caused due to crosstalk of the switches.

III. PHASE NOISE CONVERSION

Part of the input-field E_L is coupled into the second waveguide due to the crosstalk c of switch 1 (see Fig. 2). This light is delayed by τ and coupled back into the signal path producing a RIN of the output signal E_T due to phase noise conversion. Restricting the analysis to phase fluctuations, only the output power $P_T = |E_T(t)|^2$ of the interferometer is

$$P_T(t) = P_o\{1 + c^4 + 2c^2 \cos[\phi_o + \Delta\phi(t,\tau)]\}. \tag{4}$$

The term $\phi_o = \langle\omega\rangle\tau$ represents the mean phase difference between the two interferometer arms [5]. The phase change $\Delta\phi(t,\tau)$ is the fluctuating phase term resulting from the interference of the two beams after a TD τ. It is assumed that the delay-time $\tau \ll t_c$, which is the coherence time of the source. An assumption which limits τ to values of about 600 ps if a distributed feedback (DFB) laser is used as a source ($\Delta\nu \approx 50$ MHz). Using the formalism of [5], we get

$$P_T(t) = P_0\{1 + c^4 + 2c^2 \Delta\phi(t,\tau)\} \tag{5}$$

if the delay-time τ is $T/4$ (T: period of the microwave signal with $\omega_m = 2\pi/T$). The mean phase difference between the two waves is $|\phi_o| = \pi/2$ and the transfer from phase noise of the laser to intensity noise reaches its maximum value. If the noise spectrum of the transmitted power P_T is measured, one

$$\mathbf{P_{out}} = \mathbf{SW} \cdot \mathbf{P_{in}} = \begin{bmatrix} s\cdot d\cdot(1-c) + (1-s)\cdot d\cdot c & s\cdot d\cdot c + (1-s)\cdot d\cdot(1-c) \\ s\cdot d\cdot c + (1-s)\cdot d\cdot(1-c) & s\cdot d\cdot(1-c) + (1-s)\cdot d\cdot c \end{bmatrix} \cdot \begin{pmatrix} P_{11} \\ P_{12} \end{pmatrix} \tag{1}$$

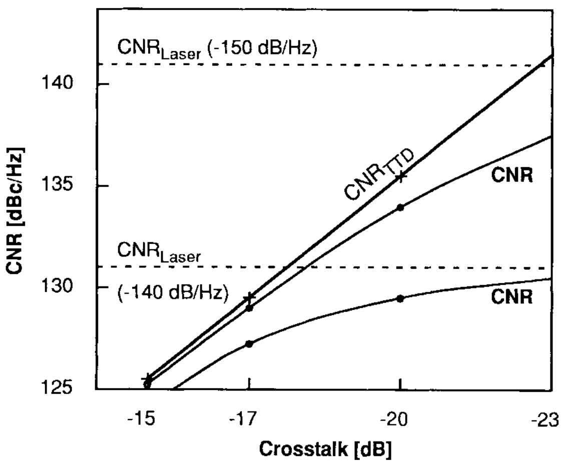

Fig. 3. CNR limited by $\mathrm{RIN}_{\mathrm{Laser}}$ or RIN generated in the TTD-network $\mathrm{CNR}_{\mathrm{TTD}}$ ($\mathrm{RIN}_{\mathrm{Laser}} = -140$ or -150 dB/Hz).

also obtains the noise spectrum for the phase-change $W_{\Delta\phi}$. The spectral density of $W_{\Delta\phi}$ is related to the spectral density of the frequency noise W_f as [5], [6]

$$W_{\Delta\Phi}(\omega_m) = W_f(\omega_m) \cdot \frac{\sin^2(\omega_m \tau/2)}{(\omega_m/2)^2}. \tag{6}$$

With the noise signal $|\Delta P|^2 = P_0^2 4c^4 |\Delta\phi^2|$ and the noise bandwidth Δf, the intensity noise of the transmitted power $P(t)$ is given as

$$\mathrm{RIN} = \frac{\langle \delta P^2 \rangle}{\langle P \rangle^2} = 2\Delta f \frac{\langle |\Delta P(\omega_m)^2| \rangle}{P_0^2 (1+c^4)^2} = \frac{4c^4}{(1+c^4)^2} 2\Delta f \cdot W_{\Delta\phi}. \tag{7}$$

Under the assumption of noise frequencies $\ll 1/\tau$, (6) yields $W_{\Delta\phi} = \tau^2 W_f$. For small values of crosstalk c and a white frequency noise, we get

$$\mathrm{RIN} \approx 8\pi c^4 \tau^2 \Delta\nu \Delta f. \tag{8}$$

For example, a crosstalk of -20 dB and a laser linewidth of 100 MHz results in a RIN of ≈ -152 dB/Hz.

This RIN is generated in each stage of the TTD device. Under the assumption that the noise generation in each stage is an independent process, the RIN at the output of a N-b TTD device is given by

$$\mathrm{RIN}_{\mathrm{TTD}} = \sum_{n=1}^{N} \mathrm{RIN}_n \cdot d_{\mathrm{st}}^{(N-n)} \tag{9}$$

where RIN_n is the RIN generated in stage n and d_{st} represents the losses of a stage.

The achievable carrier-to-noise ratio (CNR) in our distribution system (Fig. 1) is limited by the RIN of the laser source $\mathrm{RIN}_{\mathrm{Laser}}$ or the RIN generated in the TTD network $\mathrm{RIN}_{\mathrm{TTD}}$ as follows:

$$\mathrm{CNR}_{\mathrm{Laser,\,TTD}} = \frac{1}{\Delta f} \frac{m^2}{2 \cdot \mathrm{RIN}_{\mathrm{Laser,\,TTD}}} \tag{10}$$

where m is the modulation index. In Fig. 3, the CNR and the maximum achievable limits given by $\mathrm{CNR}_{\mathrm{Laser}}$ and $\mathrm{CNR}_{\mathrm{TTD}}$ are shown for two levels of RIN of the laser source -140 and -150 dB/Hz.

In our experiment, $\mathrm{RIN}_{\mathrm{Laser}}$ is $\approx 10^{-14}$ and the modulation index is $m = 0.5$. In the integrated optic-TTD device with ≈ -17-dB crosstalk of the optical switches, a $\mathrm{RIN}_{\mathrm{TTD}} \approx 14 \cdot 10^{-15}$ is generated and is, therefore, limiting the CNR.

In a phased-array antenna for satellite-communication applications, a phase error of less than 5° between two subarrays is required where 2° can be produced in the beamforming network [7]. With a system bandwidth of 72.3 MHz (131 Mb/s), the required CNR is 120 dBc/Hz including a 7-dB system margin. The RIN produced by one stage of a TTD network should be below 10^{-14} to 10^{-15} yielding a crosstalk requirement of less than -20 dB for each optical switch.

IV. Summary

Three effects in the TTD network on the phase error of the microwave signal are investigated. First, the influence of the crosstalk signals originated in each switch is investigated using a transfer matrix model of the TTD network. With the same model, the inaccuracy of the length of the waveguides is considered. For crosstalk levels below -19 dB, the phase error of the microwave signal is less than the required 2°. The third contribution to the phase error is the degradation of the CNR caused by phase noise conversion in the stages of the TTD network. For integrated optical solutions, a crosstalk less than -20 dB for each switch is required. Delay times of several hundred picoseconds or nanoseconds, as used for the calibration of radar systems, must be implemented with hybrid solutions [4]. Here, the accuracy of the fiber length and the estimation of the group velocity in the fiber are the main factors determining the phase accuracy of the system.

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