# Phased-Array Optically Controlled Receiver Using a Serial Feed

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***Abstract*—Extension of a new optically controlled serially fed phased-array system to the receive mode of operation has been demonstrated. Our system uses the pulsed nature of microwave radars in a manner similar to clocked systems used in digital configurations. This novel approach requires only the use of one tunable laser, one optical modulator, and one chirped fiber grating unit. In this letter, we present an experimental demonstration of a two-element serially fed wide frequency range receiver that validates the feasibility of this novel concept. Our system can be readily expanded with multiple elements and transmit/receive modules for a complete phased array system.**

***Index Terms*—Directional communications, fiber gratings, optical control, optical fiber delay line, phased-array radar.**

## I. Introduction

WE HAVE recently reported the development of a novel optically controlled phase array transmit configuration, suitable for numerous applications, including phased array radar and directional data communications [1]–[3]. The serial-feed concept used in these systems represented a departure from conventional parallel-feed approaches, which are very laser intensive [4]–[14]. Our system's use of a single wavelength tunable laser, one modulator, and one fiber grating time delay element provided a major simplification in the number of required optical components. In this letter, we report the demonstration of the receive portion of this concept using a two-element receiver with observation directions ranging from $+30°$ to $-30°$. The dependence on one time delay unit to provide time/phase shifts for all of the antenna elements distinguishes this serially-fed system from previously implemented receive systems [13], [15]. Our introduction of a chirped fiber grating to the system enhances its capability by making its directional operation continuously variable. Combined with our transmit capability [1], and with the use of a T/R switch, this new design can now be extended to a complete transmit/receive radar system.

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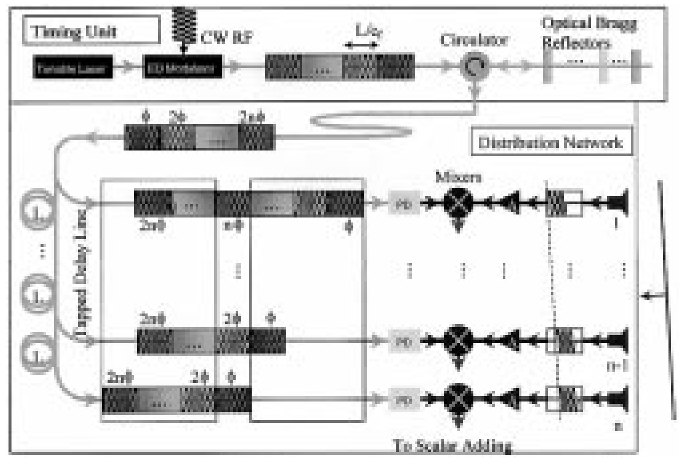


Fig. 1. Basic serially fed receive mode configuration for an array of $n$ elements. A chirped fiber grating in conjunction with a tunable laser provides the necessary phased delays for virtually continuous directional operation. A second tapped delay line in parallel can be added to achieve almost continuous temporal operation.

## II. Serially Fed Receiver Configuration

The serially fed receiver consists of a timing unit and a serial to parallel conversion distribution network as shown in Fig. 1. The timing unit sequentially generates delays designated for a given direction of observation. The distribution network then transforms these delays into parallel signals and feeds them to the antenna elements.

In the basic receive configuration (Fig. 1), the train of $(L/c_f)$-long laser light pulses, where $L$ is the tapped fiber delay length and $c_f$ is speed of light in fiber, is modulated at the desired microwave frequency, and directed through an optical circulator to a fiber grating. By reflecting from a particular point on the fiber grating a wavelength-selected phase shift is imposed onto each modulated optical pulse. The returned light from the third port of the circulator enters the distribution network which supplies each mixer with the local oscillator (LO) signal for mixing with the received microwave signal. Assume that the tapped delay line is loaded sequentially with $2n$ pulses from a tunable laser each carrying the LO signals that are phase shifted by $\phi, 2\phi, \cdots, 2n\phi$, respectively, to the mixers. The tunable laser must switch wavelengths on the order of a $ns$ and therefore has little effect on typical radar signals which have durations of hundreds, and even thousands, of nanoseconds. At the beginning of the receive mode of operation, the first pulse supplies the last mixer and the $n$th pulse supplies the first mixer. After an interval $L/c_f$ in

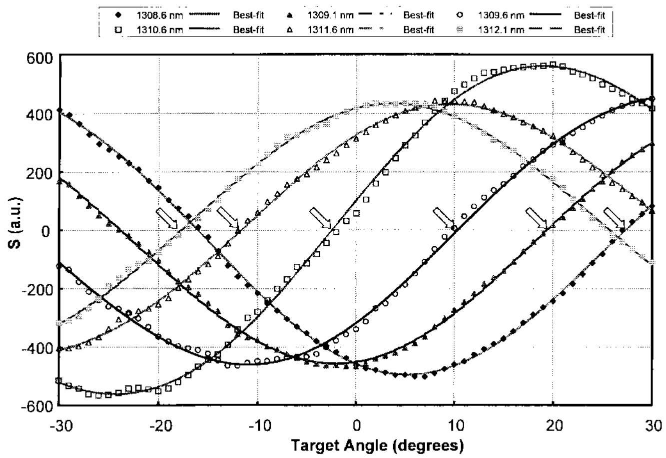


Fig. 2. Target scanning with the receiver pointed to six different "listening" directions, defined by the tunable laser wavelength $\lambda_t$. In this demonstration, experimentally determined "listening" directions correspond to the angles where $S = 0$ and $S' > 0$.

time, the second pulse will reach the $n$th mixer and become its LO signal carrier. At the same time, the $(n+1)$th pulse will be supplying the first mixer and the cycle continued. Note that the receiver continues to "listen" in the same direction after each wavelength progression because only the relative phases between mixers (differential phase $\phi$) are important. This wavelength progression repeats until the last loaded pulse reaches the first mixer.

At this point, there would be a loss of duty cycle for the simplest configuration while the line is reloaded. However, in order to achieve almost continuous operation, our design can incorporate the option of a second tapped delay line with an extra $nL$ delay length which can be switched to feed each mixer the appropriate phase. Although, as in our initial transmit experiment a two-laser switch system was used, we have utilized a linearly chirped grating, which along with a tunable DBR laser will provide almost continuous scanning for the ultimate system.

## III. EXPERIMENT

In an experimental demonstration with a two-element array, we used two external cavity wavelength tunable lasers in conjunction with two optical modulators to simulate a single fast tunable laser. The wavelength of the first laser was fixed at $\lambda_f$ and the wavelength $\lambda_t$ of the second laser was tuned to different values to control the "listening" direction of the receiver. A continuously chirped fiber grating centered at 1310 nm with a 10-nm bandwidth (>97% reflectivity) was used as the wavelength sensitive element. Phase delayed signals corresponding to the reflections of $\lambda_f$ and $\lambda_t$ were generated by the basic true time delay (TTD) timing unit used in the transmit configuration and, therefore, yielded squint-free operation. An RF signal was simultaneously fed to a transmitting horn placed on a rotating stage to simulate the signal returned from a target. The RF signal picked up by each of the receiving antenna elements was fed to the RF port of a mixer. The LO input of the mixer at each element was provided with the phase delayed signal from the timing unit and photodiode. Because the target distance was considered unknown, quadrature mixers were used to provide homodyne IF signals in two quadrants. The two outputs of the mixer associated with the first antenna element contain dc components given by

$$V_{\sin}^{\mathrm{I}} = A_{\mathrm{I}} B_{\mathrm{I}} \sin(\phi - \Phi_1) \quad V_{\cos}^{\mathrm{I}} = A_{\mathrm{I}} B_{\mathrm{I}} \cos(\phi - \Phi_1).$$

For the outputs of the mixer associated with the second antenna element, we have

$$V_{\sin}^{\mathrm{II}} = A_{\mathrm{II}} B_{\mathrm{II}} \sin(\Delta - \Phi_1) \quad V_{\cos}^{\mathrm{II}} = A_{\mathrm{II}} B_{\mathrm{II}} \cos(\Delta - \Phi_1)$$

where $A_{\mathrm{I}}$ and $A_{\mathrm{II}}$ are proportional to the LO amplitudes sent to the mixers, $B_{\mathrm{I}}$ and $B_{\mathrm{II}}$ are proportional to the received RF amplitudes, $\Phi_1$ is an unknown phase in the received RF signals due to the unknown target distance, $\phi$ is the phase difference between the LO signals (from the timing unit), $\Delta = (d\omega \sin\theta)/c$ is the phase difference between the received RF signals due to the different path lengths from the target, $\theta$ is the target angle, and $d$ is the spacing between the antenna elements. The four outputs of the mixers were fed to a computer for processing. The computer calculated the final result in the form

$$S = V_{\cos}^{\mathrm{I}} \cdot V_{\sin}^{\mathrm{II}} - V_{\sin}^{\mathrm{I}} \cdot V_{\cos}^{\mathrm{II}} = A_{\mathrm{I}} A_{\mathrm{II}} B_{\mathrm{I}} B_{\mathrm{II}} (\Delta - \phi). \quad (1)$$

The phase difference between the LO signals is set in the timing unit by the fiber grating for each wavelength pair $\lambda_f - \lambda_t$ and is described by

$$\phi = k(\lambda_t - \lambda_f)\omega$$

where $k$ is a parameter involving the chirp of the fiber grating. For a given target direction, $\theta$ can be extracted by plotting $S[\phi(\lambda_t)]$ for different $\lambda_t$. The calculated function $S$ in (1) is zeroed, with a positive slope, when $(d \sin\theta)/c = k(\lambda_t - \lambda_f)$. Therefore, the target angle can be written as

$$\theta = \sin^{-1}[ck(\lambda_t - \lambda_f)/d]. \quad (2)$$

In this feasibility demonstration, the receiver had only two elements and to increase the resolution of the system, we had chosen to use the function $S$ in (1) to determine the target angle because of its sensitivity near $(d \sin\theta)/c = k(\lambda_t - \lambda_f)$.

To demonstrate the ability of the system as a phased array radar receiver, we chose six different wavelength pairs to deliver the LO signals; effectively, the receiver was used to "listen" to six different directions. For a selected direction (wavelength pair), the target angle was changed from −30° to 30° with a step size of 1°. As shown above at the right "listening" direction the $S$ function is zero with a positive slope. In these experiments, the RF frequency was set to 8 GHz, $\lambda_f$ was kept at 1310.6 nm and $\lambda_t$ was tuned to six different wavelengths. Fig. 2 shows the corresponding $S$ function versus the target angle for each wavelength pair. The least square best-fit functions were calculated and used to determine the target directions with higher accuracy. The measured target angles (corresponding to the angles where $S = 0$ and $S' > 0$ in Fig. 2) are −17.7°, −11.6°, −2.4°, 10.4°, 19.4°, and 27.4°. The theoretically calculated six "listening" directions, using (2), are −19.3°, −12.8°, 0°, 12.8°, 19.3°, and 26.2°. The measured values are well within the expected 3° of the two antenna element theoretical values.

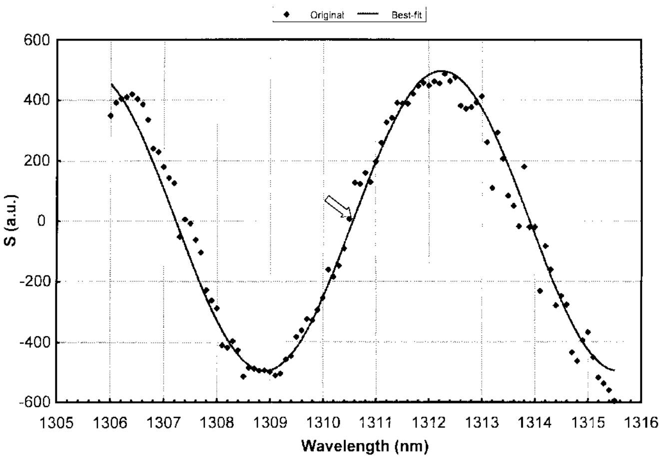


Fig. 3. Wavelength scanning with the target located at 0° and the fixed wavelength $\lambda_f = 1310.55$ nm. Using a best-fit function to the sine function, the experimentally determined target direction is $\theta = 0.6°$.

In another experimental modality to demonstrate the capability of changing the "listening" direction continuously, the target angle was fixed at 0° and $\lambda_f$ was set to 1310.6 nm. The wavelength $\lambda_t$ was then scanned from 1306.0 to 1315.5 nm with a step size of 0.1 nm determined by the resolution of the tunable laser. The $S$ function versus the wavelength $\lambda_t$ is shown in Fig. 3. The solid line is the best-fit sine-function that has a zero value (with a positive slope) at the wavelength $\lambda_t = 1310.60$ nm corresponding to 0.6° according to (2). The results show excellent agreement with predictions and indicate that the serial system works well in the receive mode.

## IV. Conclusion

We have successfully demonstrated a receive mode operation of a serially fed optically controlled phased array system. It uses the same basic elements as the previously reported transmitter and completes the serial system.

For a practical system with multiple elements, the mixer outputs would be processed in the following way:

$$M = \left(\sum_i V_{\cos}^{(i)}\right)^2 + \left(\sum_i V_{\sin}^{(i)}\right)^2. \tag{3}$$

When the signal arrives in from the desired direction, the angular phase dependency is removed by mixing with the selected LO signals for that direction; the scalar function $M$ is maximized by this process. In a radar application, this scalar signal $M$ can then be used to determine the target distance. In a practical multiple-element radar system, the beam width will be much narrower than that of our two-element array. Therefore, the $M$ function in (3) can be used to sum the mixer outputs together for further processing. $M$ will be maximized as a sharp peak only at the selected direction because the mixer outputs are "in phase" at this receive angle and "out of phase" elsewhere.

In a pulsed transmit/receive radar system, once a RF pulse has been transmitted, the system has to switch to the receive mode to listen for the echo. The conjugate differential phase $(\phi)$ of that used in transmit $(-\phi)$ is now used in the receive mode since the mixers generate a difference frequency and subtract the phases of the two input signals to be used in forming the scalar quantity $M$. This phase requirement can be achieved by using the fiber grating in the reverse direction or by using the transmit wavelengths in reverse order. This technique provides the wide frequency range squint-free receiver steering since real-time delays, generated in the fiber grating, are used to obtain the phase angles.

The extension of the two-element serially fed optically controlled system to the receive mode has been presented. Of greater importance, however, is that it is now possible to implement the concept of a serial feed in a complete radar system, which will require a transmit/receive switch module and a dual feed line for a continuous operation. Finally, because of its simplicity and the significant reduction in the number of optical components, this system has major advantages over proposed conventional parallel configurations and is one of the few which have actually been demonstrated [13], [15].

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