OPTICALLY CONTROLLED SERIALLY FED PHASED ARRAY RADAR

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Abstract

We have developed and tested a new optically controlled serially fed system suitable for phased array radar applications. This system uses a serial-feed concept that represents a new departure, in radar applications, that will yield a major simplification in both optical and microwave components. Unlike many systems, which use a parallel approach, our system with both phase and true time delays requires but a single tunable laser, modulator and time delay element.

Serially Fed Transmitter Configuration

The transmit function can be best described in terms of a timing unit and a distribution network as shown on Fig. 1. The desired delays for a given RF beam direction are generated sequentially by the timing unit and then transformed into parallel signals to feed the antennas by the distribution network.

The timing portion uses an electrically tuned DBR laser which is amplitude modulated with the desired microwave pulses using an optical modulator. After the modulator the laser light is directed through an optical circulator to a fiber optic grating.

The grating reflects light back at different positions along the fiber depending upon the optical wavelength. In the basic system discussed here, each serially-fed optical pulse has a unique wavelength and therefore a unique time delay, relative to the RF pulse gate, which has been chosen to produce a given pointing

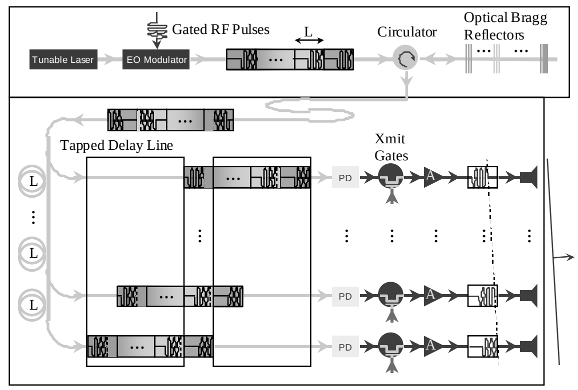

Figure 1.

direction. The number of pulses in the fully loaded tapped delay line corresponds to the number of radiating elements in the array or subarray. The RF amplitude and phase of each element can be controlled independently, therefore multi-beam patterns can be formed using the same hardware configuration.

Returned light from the third port of the circulator enters the distribution network formed by the tapped delay line. It is important to note that this delay line is used to transform serial signals into parallel ones, and does not generate the delays for beam steering. Once the series of optical pulses arrive at the correct delay line tap for each antenna element, the microwave modulation is obtained using photodetectors. The microwave signals from these detectors are simultaneously gated on with microwave switches (Xmit gates) when the tapped delay line is fully loaded. Each element's microwave pulse has the correct time delay set by the fiber grating to form a radiating beam in the desired direction. After the signal is

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radiated the switches are turned off and the line is reloaded. The number of radiating directions is limited only by the number of available laser wavelengths and Bragg reflectors.

Transmit mode Demonstration

We have built a two-element transmitter with five optical wavelengths thus giving us five pointing directions. One external cavity tunable laser (wavelength = λ_t) and one fixed wavelength laser (wavelength = λ_f) were used in conjunction with two optical modulators to generate the wavelengths needed. By pulse gating and RF modulating the CW λ_t and λ_f signals alternately, a fast tunable laser switching between two wavelengths (λ_t and λ_f) was simulated. The five values of λ_t were from 1307.50 nm through 1311.50 nm, separated by 1 nm. λ_f was set at 1309.50nm.

The radiation node direction was measured by moving the receiving horn around with the same distance from the two-element array until the received signal was minimized. Using an antenna separation 2.54cm, the theoretical node directions are -28°, -14°, 0°, 14°, and 28°. Fig. 2 shows the measured node direction vs. RF frequency at different optical wavelengths with 10 ns pulses. It illustrates squint-free operation with some minor fluctuations.

To demonstrate the wide instantaneous bandwidth of the transmitter, the 10 GHz, 1 ns pulses were radiated and again the radiation node directions were measured. These node directions are the same as those in Fig. 2. The spectra of the received signals at a node were measured. Because of the extra π phase shift introduced by biasing the optical modulators, the signals from the two antennas interfered destructively resulting a low power level from 8 GHz through 12 GHz. To further demonstrate the two antenna signals cancel out, one antenna was disconnected from the system and the spectrum of the other antenna was measured. It is clear that destructive interference occurred from 8.5 GHz through 11.5 GHz when both antennas were radiating.

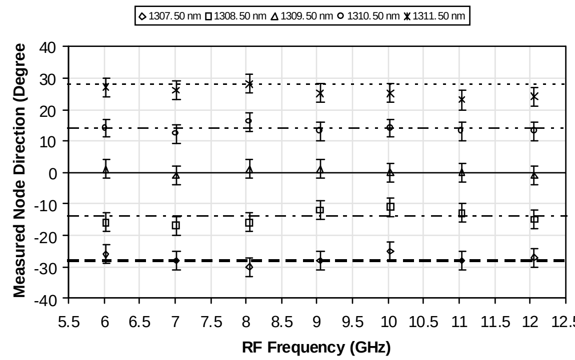

Figure 2.

This demonstrates the wide instantaneous bandwidth of the transmitter.

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.3.

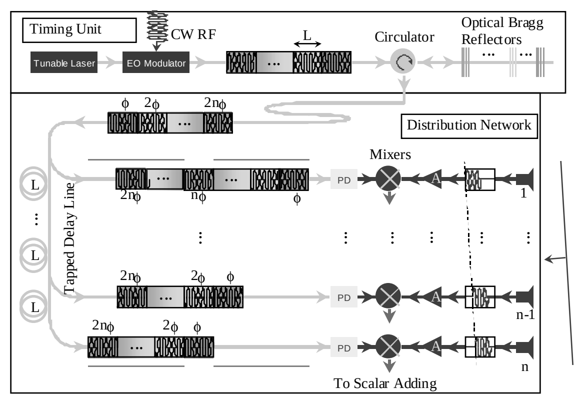

Figure 3.

In the basic receive configuration, 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 ϕ, 2ϕ, …, $2n\phi$, respectively, to the mixers. 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 time, the second pulse will reach the nth 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 ϕ) 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.

Receiver Demonstration

We again 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 λ_f and the wavelength λ_t of the second laser was tuned to different values to control the "listening" direction of the two-element receiver. By alternatively RF modulating the CW λ_f and λ_t signals, a fast tunable laser switching between two wavelengths was effectively simulated. 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 λ_f and λ_t were generated by the basic true time delay (TTD) timing unit used in the transmit configuration and, therefore, yielded squint-free operation. A RF signal was simultaneously fed to a transmitting horn placed on a rotating stage to simulate the signal returned form 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, the returning signal and the LO could be out of phase resulting in zero output. To avoid this problem, quadrature mixers were used to provide homodyne IF signals in two quadrants.

The four outputs of the mixers were fed to a computer for processing. The computer calculated the final result in the form: $S = V^{I}_{\cos} \cdot V^{II}_{\sin} - V^{I}_{\sin} \cdot V^{II}_{\cos} = A_I A_{II} B_I B_{II} \sin(\phi - \Delta)$, (Eq.1), where A_I and A_{II} are proportional to the LO amplitudes sent to the mixers, B_I and B_{II} are proportional to the received RF amplitudes, ϕ 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, θ is the target angle, and d is the spacing between the antenna elements.

The phase difference between the LO signals is set in the timing unit by the fiber grating for each wavelength pair λ_f - λ_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, θ can be extracted by plotting $S[\phi(\lambda_t)]$ for different λ_t. The calculated function S in Eq. (1) is zeroed, with a positive slope, when $(d \sin\theta)/c = k(\lambda_t - \lambda_f)$. To increase the resolution of the system, we had chosen to use

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the function S in Eq. (1) to determine the target angle because of its sensitivity near $(d \sin \theta)/c = k(\lambda_t - \lambda_f)$ (Eq.2).

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, λ_f was kept at 1310.6 nm and λ_t was tuned to six different wavelengths. Fig. 4 shows the corresponding S function versus the target angle for each wavelength pair.

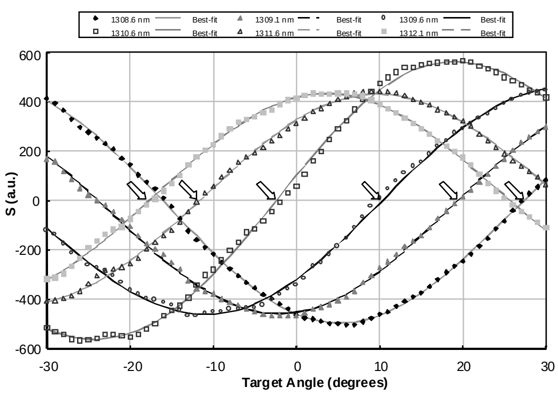

Figure 4.

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. 3) are -17.7^0, -11.6^0, -2.4^0, 10.4^0, 19.4^0 and 27.4^0. The theoretically calculated six "listening" directions, using Eq. (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 theoretical values. Because this experimental receiver has only two elements, its beam width is very broad (~60°) and accounts for most of the angular uncertainty.

Conclusion

We have successfully demonstrated transmit and receive mode operation of a serially fed optically controlled phased array system. The decrease in the number of necessary components to a single tunable laser, optical modulator, and a delay fiber grating considerably simplifies and improves the design of optically controlled phased arrays.

To extend our basic serial feed to 2D, a ladder version of the distribution network (Fig.1 and 3) may be implemented. The initially investigated system had constraints that limited its straightforward extension to relatively large arrays. In our new variation all of the splitters are implemented in a symmetric configuration which lends itself to economical production and scaling. The basic unit for the 4 x 4 antenna subarray control will use a 1 x 4 power splitter in series with four 1 x 4 splitters as shown in Fig. 5. The ladder concept permits us to use symmetric splitters at each junction. It also reduces the power density in each line and permits a very much simpler approach in filling in a large antenna array. Finally, we note that this concept has the advantage of reducing a very specialized distribution network to a very simple, relatively inexpensive set of series and parallel power splitters.

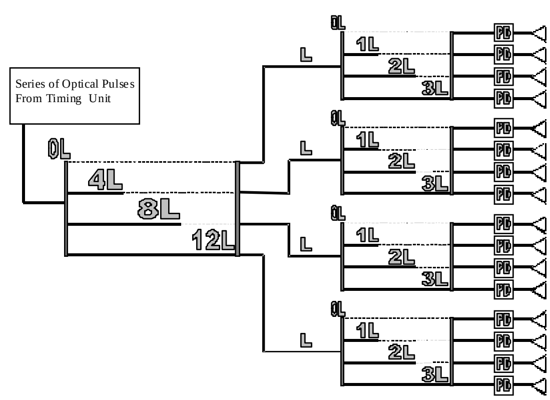

Figure 5.

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