Optically Controlled Serially Fed Phased-Array Transmitter

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***Abstract*— A new optically controlled phased-array system has been developed that has all the advantages of true time delay (TTD), yet only requires one tunable laser, one optical modulator, and one fiber-optic grating unit. In this letter, a two-element serial-feed transmitter has been assembled and tested to demonstrate the feasibility of this novel concept. Experimental results include TTD operation from 6–12 GHz using both 10- and 1-ns pulses transmitted to five different directions.**

***Index Terms*—Optical control, phased array, serial feed, true time delay.**

I. Introduction

We have developed a new optically controlled system, suitable for phased array radar, microwave imaging, directional data communication, and related applications [1], [2]. This system uses a serial-feed concept that represents a departure from the conventional approach to these applications. Our concept yields a major simplification in both optical and microwave components. Unlike many of the parallel systems [3]–[8] currently under investigation, our system requires a single wavelength tunable laser, modulator, and time delay element [9] to provide the necessary phase and true time delays. In our design the use of fiber-optic techniques, such as long and low-loss delay lines, is intrinsic to operation of the system. Precise timing control is used to distribute RF pulses with phase and time delay information to each element in an operating antenna array. In this letter we report a demonstration of this concept using a two-element transmitter with five pointing directions. We also exhibit true time delay (TTD) operation from 6–12 GHz.

II. Serial-Feed Configuration

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

Manuscript received September 23, 1996. This work was supported by the Air Force Office of Scientific Research and by the National Center for Integrated Photonic Technology under DARPA Contract MDA972-94-1-0001.

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Publisher Item Identifier S 1051-8207(97)01772-8.

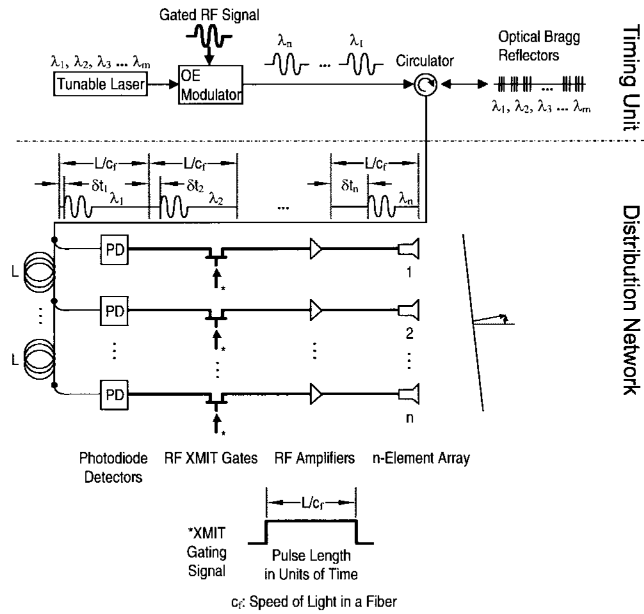

Fig. 1. Basic serial-feed transmit mode implementation for array of n elements. An optical Bragg grating unit in conjunction with a tunable laser provides steering delays.

In our design, the timing portion uses an electrically tuned DBR laser [10], [11]. The laser light output is both amplitude modulated at the desired microwave frequencies and gated at the RF transmission signal pulse length using an optical modulator. After passing through the modulator, the laser light is directed through an optical circulator to a series of fiber-optic Bragg reflectors. The incident optical wavelength determines the position in the fiber at which light is reflected back. Thus, a wavelength-selective delay can be imposed onto each RF modulated optical pulse. In the basic system discussed here, each serially fed optical pulse has a unique wavelength and therefore a unique time delay relative to the gating signal. The desired pointing direction determines which wavelengths should be chosen. The number of pulses in the fully loaded tapped delay line corresponds to the number of radiating elements in the antenna array or subarray. Specifically, the first pulse is intended for the nth element and the nth pulse is intended for the first element. The RF amplitude and phase of each element can be controlled independently, thus allowing multibeam patterns to 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 tapped 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 taps for each antenna element, the microwave modulation is extracted using photodetectors. When the tapped delay line is fully loaded, the microwave signals from these detectors are simultaneously gated on with microwave switches (Xmit gates). Each element's microwave pulse has the correct time delay set by the timing unit to form a radiating beam in the desired direction. After the signal is 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. Although our initial efforts used a two laser switched system and a fiber grating unit with discrete wavelength selectivity, the system will ultimately use a tunable DBR laser with a linearly chirped grating to provide continuous scanning.

III. Experiment

To establish the viability of this serial-feed approach, we have assembled a two-element transmitter with five optical wavelengths yielding five discrete pointing directions. One external cavity tunable laser $(\mathrm{wavelength} = \lambda_t)$ and one fixed wavelength laser $(\mathrm{wavelength} = \lambda_f)$ are used in conjunction with two optical modulators to generate the desired wavelengths. By alternately pulse gating and RF modulating the CW λ_t and λ_f signals, a fast tunable laser switching between two wavelengths (λ_t and λ_f) is effectively simulated. In our initial experiments the repetition rate of wavelength switching was 25 MHz, corresponding to the tapped fiber delay length $L \approx 4$ m. The five values of λ_t varied from 1307.50 nm through 1311.50 nm, with a 1-nm separation between wavelengths, and λ_f was set at 1309.50 nm. These wavelengths were selected based on the Bragg wavelengths of the fiber reflectors. The relative time delays between the λ_t pulses and the λ_f pulse were measured to be -40 ps, -20 ps, 0 ps, 20 ps, and 40 ps, with an uncertainty of ± 2 ps.

The time-delayed RF signals feeding the two-element antenna array were monitored on a digital sampling oscilloscope's (DSO's) channel 1 and 2 (CH1 and 2). By correctly gating the RF signals exiting the photodetectors, CH1 received the λ_t pulse (variable delay) and CH2 received the λ_f pulse (delay reference). Two representative pulse widths have been tested: 10 and 1 ns. The 10-ns pulses offer a flat middle portion suitable for time-delay measurements using our DSO with best-fit sine functions. The time delays measured using the two channels of the DSO agree with the designed grating delays at RF frequencies from 6–12 GHz. The 1-ns pulses, with a 10-GHz center frequency, contained frequency components from 8–12 GHz and were suitable for demonstrating the wide instantaneous bandwidth of the system. Fig. 2 shows 10-GHz, 1-ns pulses, with two of the five possible time delays.

Because this experimental transmitter only has two elements, its radiating beam width is very broad ($\sim$60°). Therefore, in order to demonstrate squint-free operation with acceptable resolution, the radiation node was used instead of the antinode. The two optical modulators were biased at different modulation slopes to provide an extra π phase shift between the two elements. The radiation node direction was measured by moving the receiving horn to minimize the detected signal, while maintaining the same distance from the two-element array. Using an antenna separation of 2.54 cm, the theoretical node directions are $-28°, -14°, 0°, 14°$, and 28°. Fig. 3 shows the measured node direction versus RF frequency at different optical wavelengths using 10-ns-long pulses. It shows good agreement with the anticipated pointing directions and effectively illustrates squint-free operation with some fluctuations. The observed deviations are attributed to the fact that only two elements were used in this transmitter. This resulted in a large uncertainty in locating the minimum of the received signal. By using more antenna elements, direct measurements on the antinode directions will provide exceptional resolution with suppressed fluctuations.

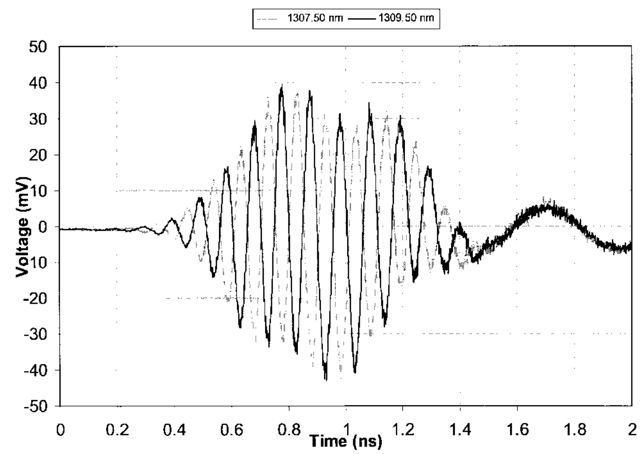

Fig. 2. Ten-GHz 1-ns pulses carried by 1307.50- and 1309.50-nm optical carriers monitored on the CH1 of the DSO. The 1307.50-nm pulse leads the 1309.50-nm pulse by 40 ps.

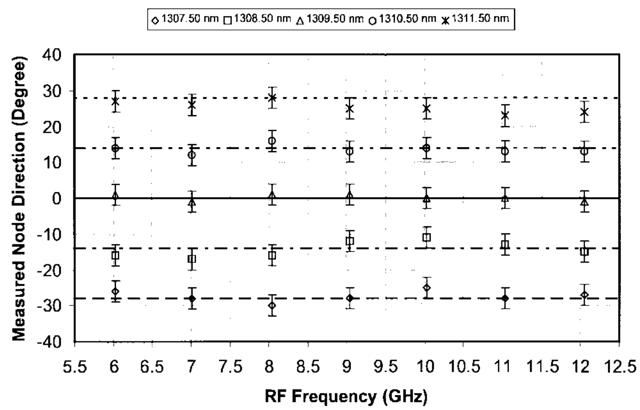

Fig. 3. Measured node direction versus RF frequency at different λ_t with λ_f fixed. The straight lines show the theoretical values. This shows the TTD nature of the system.

To demonstrate the wide instantaneous bandwidth of the transmitter, 10-GHz, 1-ns pulses with 25-MHz system repetition rate were radiated. The radiation node directions were measured to be the same as those in Fig. 3. The spectra of the

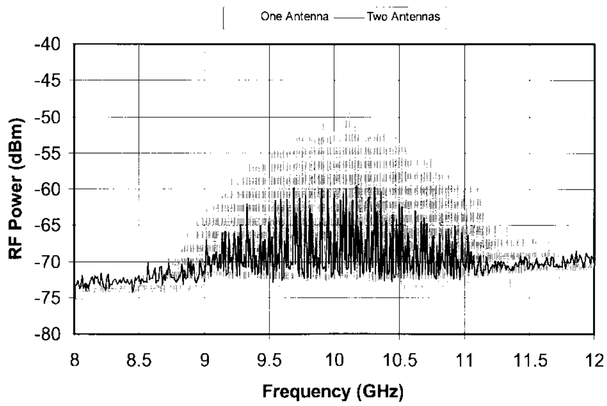

Fig. 4. The spectra of the detected 1-ns pulses centered at 10 GHz. The fine structure was caused by the system repetition rate of 25 MHz. The receiving horn was located at the node ($-28°$). The gray curve is the signal from only one antenna. The black curve shows that the signals from the two antennas cancel each other as expected for a node.

received signals at a node are shown in Fig. 4. The black curve was obtained when both antennas were radiating. Because of the TTD in our system, the node position is independent of frequency. The power spectrum of the node is shown to be minimized over the bandwidth defined by the pulse (8–12 GHz). To further demonstrate the two antenna signals indeed cancel out, one antenna was disconnected from the system and the spectrum of the other antenna measured. The result is shown as the gray curve in Fig. 4.

IV. Conclusion

A new serially fed true time delay transmit system has been presented and the basic concept has been experimentally verified. It uses only one tunable laser, one optical modulator and one delay element to achieve beam steering thereby greatly simplifying and increasing the flexibility of optically controlled systems. For large two-dimensional arrays ($>10^3$ elements), the problem of obtaining sufficient delays can be solved by cascading two timing units: one for horizontal control and one for vertical control. In such a system, consisting of two lasers, optical modulators, and delay elements, the RF modulated optical output of the vertical timing unit is detected and then fed to the RF input of the optical modulator of the horizontal timing unit. The number of delays obtainable from this configuration will go as the square of the number of wavelengths obtainable from each laser. Furthermore, a natural extension of this technology can be used both for the receive mode and for passive imaging [1].

The two-element, five-delay transmit system we have presented is a basic unit that demonstrates the concept of a serial-feed. It is possible to enhance this system in several ways and to extend it to multiple frequencies and beams. Finally, this system represents a major departure from traditional parallel connected configurations. Because of its simplicity, we foresee its implementation in many new application areas.

Acknowledgment

The authors would like to thank E. Roth at the UCLA ICSL and F. M. Espiau at the UCLA CHFE for providing technical support. They also acknowledge helpful discussions with Prof. B. Jalali and Prof. M. C. Wu.

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