A Wide-Band Fiber-Optic True-Time-Steered Array Receiver Capable of Multiple Independent Simultaneous Beams

Paul J. Matthews, Michael Y. Frankel, and Ronald D. Esman, *Senior Member, IEEE*

Abstract—A wide-band fiber-optic true-time-delay array receiver capable of receiving multiple independent beams simultaneously is demonstrated for the first time. The receiver is based on a dispersive prism technique and exhibits squint-free $\pm 60^\circ$ azimuthal steering of two simultaneous beams with no observable beam squint over a microwave component-limited bandwidth of 6–18 GHz.

Index Terms—Antenna array feeds, optical fiber delay lines, optical fiber applications, optical fiber dispersion, phased-array radar, phased arrays.

I. INTRODUCTION

PHASED-ARRAY antenna systems are currently the subject of much development activity primarily due to the inherent advantages of an electronically steered beam over a mechanically steered beam. These advantages include speed, reliability and graceful degradation. Additionally, the use of phased-array antennas permits the possibility of multiple, independent beams performing different functions simultaneously and sharing a common antenna aperture. This last aspect is becoming increasingly important for future phased-array antenna systems being currently planned. The use of shared apertures leads to increased affordability, the potential for improved system performance, as well as improved antenna siting and a reduced radar cross section.

To date, many of the advantages of phased-array antennas have not been fully realized primarily due to the limitations of traditional all-electronic control of individual array elements. The major drawbacks of current phased-array antenna systems have been size, weight, loss, and narrow instantaneous bandwidths of the signal distribution networks. Also, a true simultaneous, shared aperture concept has yet to be effectively demonstrated using any beamforming technique.

The use of optical control techniques for phased-array antennas promises to alleviate many of the problems associated with traditional all-electronic beamformers. In particular, optical techniques are able to provide the true-time-delay (TTD) beam steering necessary for squint-free, wide instantaneous bandwidth operation. Various optical TTD techniques have been proposed [1]–[3]. However, in general, the proposed tech-

Fig. 1. The fiber-optic TTD receiver schematic.

niques are not amenable to providing multiple, independent, simultaneous beams.

Here, we demonstrate the first true-time-delay control of an ultrawide-band array receiver capable of receiving and processing multiple beams simultaneously. The receiver is based on the dispersive prism technique which has been previously demonstrated in a two-dimensional (2-D) transmitter configuration [2]. This receive system demonstrates $\pm 60^\circ$ azimuthal steering of two simultaneous beams with no observable beam squint over a microwave component-limited bandwidth of 6–18 GHz. This technique is capable of being transitioned to real-world ultrawide-band shared aperture receiver systems.

II. SYSTEM CONFIGURATION

The fiber-optic receiver system is shown schematically in Fig. 1. The incident microwave energy is received by eight phase-matched spiral array elements, amplified using 6–18-GHz low-noise preamplifiers, and fed to a parallel bank of electrooptic Mach-Zehnder modulators (MZM's) which intensity modulate a wavelength-tunable optical carrier with the microwave signal. The optical carrier is provided by a tunable external cavity laser with a wavelength (λ) range of 1470–1580 nm. The optical signal is amplified using an erbium-doped fiber amplifier (EDFA) before being corporately distributed to the eight MZM's. The eight modulated optical signals are fed to an eight-channel fiber-optic dispersive prism. The prism provides a wavelength-dependent time delay for each element channel, which is proportional to the position of the corresponding element in the array. The signals are then

Manuscript received September 12, 1997; revised December 12, 1997. This work was supported by the Office of Naval Research.

The authors are with the Naval Research Laboratory, Code 5672, Optical Sciences Division, Washington, DC 20375-5338 USA.

Publisher Item Identifier S 1041-1135(98)03020-1.

optically combined and fed to a high-speed photodiode (PD) for demodulation. The output of the PD is followed by a 6–18-GHz low-noise amplifier in order to partially compensate for the fiber link losses.

Tuning the wavelength of the laser changes the group velocity of the signal propagating in each arm of the fiber-optic prism and alters the time-delay gradient across the array thus providing true-time-delay beam steering. We note here that chirped fiber gratings are capable of providing the same dispersive function and could be used in place of the dispersive fiber [4]. The microwave signals from the eight elements add coherently at the photodiode forming a tunable matched filter. By combining the signals optically instead of in the microwave regime, the system becomes susceptible to optical interference problems. This is manifested in the form of amplitude fluctuations at the output due to environmental effects on the fiber. Fortunately, optical interference can be minimized by differing the lengths of the corporate feeds to each MZM by more than the laser coherence length. With equal path lengths, amplitude fluctuations after the photodiode were approximately ± 6 dB. By implementing unequal path lengths, the amplitude variations were reduced to less than 0.1 dB.

The use of dispersion in the system results in a phase-walkoff of the modulation sidebands of the optical carrier resulting in a microwave signal loss at high frequencies. The loss is given by [5]

$$G_{\text{disp}} = 20 \log \left(\cos \left(\frac{\pi D L \lambda^2 f^2}{c} \right) \right) (\text{dB})$$

where DL is the dispersion-length product of the fiber-optic link, λ is the optical carrier wavelength, f is the microwave frequency and c is the speed of light. Since the dispersion-length product is different for each element, this manifests itself as an amplitude tracking issue for large, high frequency arrays. However, for many practical arrays, this is not a serious concern, especially since the effect is not a hard limit, but instead implies a loss of power for the edge elements giving an effective amplitude taper across the array. For a given, tolerable edge element loss, the issue may also be viewed as a system-level tradeoff between the array beamwidth and maximum frequency. The impact of this effect is very application dependent. For the system described here, approximately 7 dB of additional loss was measured at a frequency of 18 GHz for the outermost element which corresponds well with the predicted value. All other elements tracked in amplitude within 2 dB up to 18 GHz. This did not result in any qualitatively noticeable degradation of the array patterns from theoretical at 18 GHz.

The receive signal-to-noise ratio was measured to be approximately 90 dB/Hz. The system was not optimized and this figure may be significantly improved by increasing the average optical power incident on the photodetector (decreasing the total link loss) which was very low in this system. This may be accomplished with a higher power amplifier or by distributing the gain. Further improvements may be gained by driving the amplifiers harder. In general, the system will perform (i.e.,

Fig. 2. The measured and calculated receive patterns with the laser tuned for -60° azimuth radiation.

dynamic range, loss, etc.) as a typical fiber-optic link under the same conditions.

Since the dispersive prism architecture employed utilizes a single optical carrier whose wavelength provides the appropriate time-delay for a given beam, multiple independent beams may be implemented by employing additional optical sources. As depicted in Fig. 1, two tunable lasers are used in this experiment in order to demonstrate two simultaneous, independent beams.

The fiber-optic prism was fabricated in a binary “tree” type architecture using wavelength flattened 50/50 couplers. The nominal unit length of high-dispersion fiber ($D \sim -88$ ps/nmkm) was 55 m, which corresponds to a 60° angular steering with a wavelength detuning of 15 nm for the given receive array. The overall delays for each of the optical paths were equalized at a wavelength of 1550 nm using dispersion-shifted fiber (DSF). A final time-delay trim was accomplished using microwave trombones before the MZM’s. Fiber-optic attenuators were included in each array element path for amplitude matching.

The fiber-optic receiver was designed to be used in conjunction with eight matched spiral elements arranged in a sparsely populated, unequally spaced pattern. The particular array pattern was chosen so as to narrow the main beam for improved angular discrimination and to suppress grating lobes. The elements were spaced 7.5, 7.5, 7.5, 10.0, 10.0, 17.5, and 12.5 cm apart and were capable of operating over the 2–18-GHz band.

III. RESULTS AND DISCUSSION

The receive array was tested in a compact radar range. A network analyzer was used to drive a radiating horn antenna which had a 2–18-GHz bandwidth. The radiation from the horn was collimated using a microwave mirror and was detected by the fiber-optic receive system mounted on a rotation pedestal. The polarization mismatch between the radiating horn and the spiral elements resulted in a 3-dB power penalty. Receive patterns were taken over an angular span of $\pm 70^\circ$ in 0.25° increments. The full 6–18-GHz band was recorded in 1-GHz increments.

The receiver was first tested using a single laser to detect a single beam. The receiver was steered to -60° by detuning

Fig. 3. Intensity plot of the dual-beam receive pattern with the lasers tuned for 0° and 30° azimuth radiation.

the laser wavelength from the broadside setting of $\lambda = 1550$ nm by -15 nm ($\lambda = 1535$ nm). Fig. 2, shows the measured and calculated azimuthal patterns for frequencies from 6 to 18 GHz. The patterns for the various frequencies are offset for clarity. The measured patterns were normalized by the measured single element pattern of the spiral element in order to show the receiver performance independent of the chosen radiating element. The results in Fig. 2 clearly demonstrate a squint-free main beam steered to -60° over the 6–18-GHz frequency range. Good agreement is observed between the measured and ideal receive patterns over the full frequency range. Due to the sparsely populated array pattern chosen, the sidelobe levels are at the -10 - to -15 -dB level near the main lobe and increase to a -5 -dB level further away. Similar results were obtained at various other steering angles over a $\pm 60^\circ$ azimuthal range.

Next, the capability for multiple, simultaneous beams was demonstrated. The two lasers were tuned to 1550 and 1558.8 nm corresponding to beams at 0° and 30° , respectively. The measured antenna patterns are shown in Fig. 3 which depicts an intensity plot of the received radiation as a function of azimuth and frequency. Both main lobes are readily discernible and exhibit squint-free operation over the full 6 to 18 GHz frequency range. The two beams are capable of being steered independently simply by tuning the wavelengths of the two lasers. This is demonstrated by tuning one beam from its position at 0° to -30° by tuning the laser wavelength from 1550 to 1541.2 nm. The results are shown in Fig. 4. The high sidelobe levels of the two beams due to the sparsely populated

Fig. 4. Intensity plot of the dual-beam receive pattern with the lasers tuned for -30° and 30° azimuth radiation.

array pattern make it somewhat difficult to distinguish the two narrow main beams. However, the main beams can now be seen at -30° and 30° and again exhibit no observable beam squint. Various other beam steering angles were chosen for the two beams yielding similar results.

IV. CONCLUSION

We have demonstrated the first wide-band array receiver capable of receiving and processing multiple beams independently and simultaneously. The receiver demonstrates $\pm 60^\circ$ azimuthal steering of two simultaneous beams with no observable beam squint over a microwave component-limited bandwidth of 6–18 GHz. Good agreement is observed between the measured and calculated receive patterns. Extension to more than two beams is readily supported through the incorporation of additional lasers.

REFERENCES

- [1] H. Zmuda and E. N. Toughlian, *Photonic Aspects of Modern Radar*. Boston, MA: Artech House, 1994.
- [2] M. Y. Frankel, P. J. Matthews, and R. D. Esman, "Two-dimensional fiber-optic control of a true time-steered array transmitter," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2696–2702, Dec. 1996.
- [3] ———, "Fiber-optic true time-steering of an ultrawideband receive array," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 1522–1526, Aug. 1997.
- [4] J. E. Roman, M. Y. Frankel, P. J. Matthews, and R. D. Esman, "Time-steered array with a chirped grating beamformer," *Electron. Lett.*, vol. 33, no. 8, pp. 652–653, Apr. 1997.
- [5] B. Christensen, J. Mark, G. Jacobsen, and E. Bodtker, "Simple dispersion measurement technique with high resolution," *Electron. Lett.*, vol. 29, pp. 132–134, Jan. 1993.