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Riza, Nabeel

Nabeel A. Riza, "Acousto-optic null-steering adaptive photonic processor architectures for phased arrays," Proc. SPIE 2754, Advances in Optical Information Processing VII, (12 June 1996); doi: 10.1117/12.243117

Event: Aerospace/Defense Sensing and Controls, 1996, Orlando, FL, United States

Acousto-optic Null Steering Adaptive Photonic Processor Architectures for Phased Arrays

Nabeel A. Riza
Center for Research and Education in Optics and Lasers (CREOL)
and the Department of Electrical and Computer Engineering
University of Central Florida
4000 Central Florida Boulevard, P. O. Box 162700
Rm 280, Orlando, FL 32816-2700
email: riza@creol.ucf.edu

Keywords: Acousto-optic processor, Null Steering, Adaptive, Phased Array Antennas

ABSTRACT

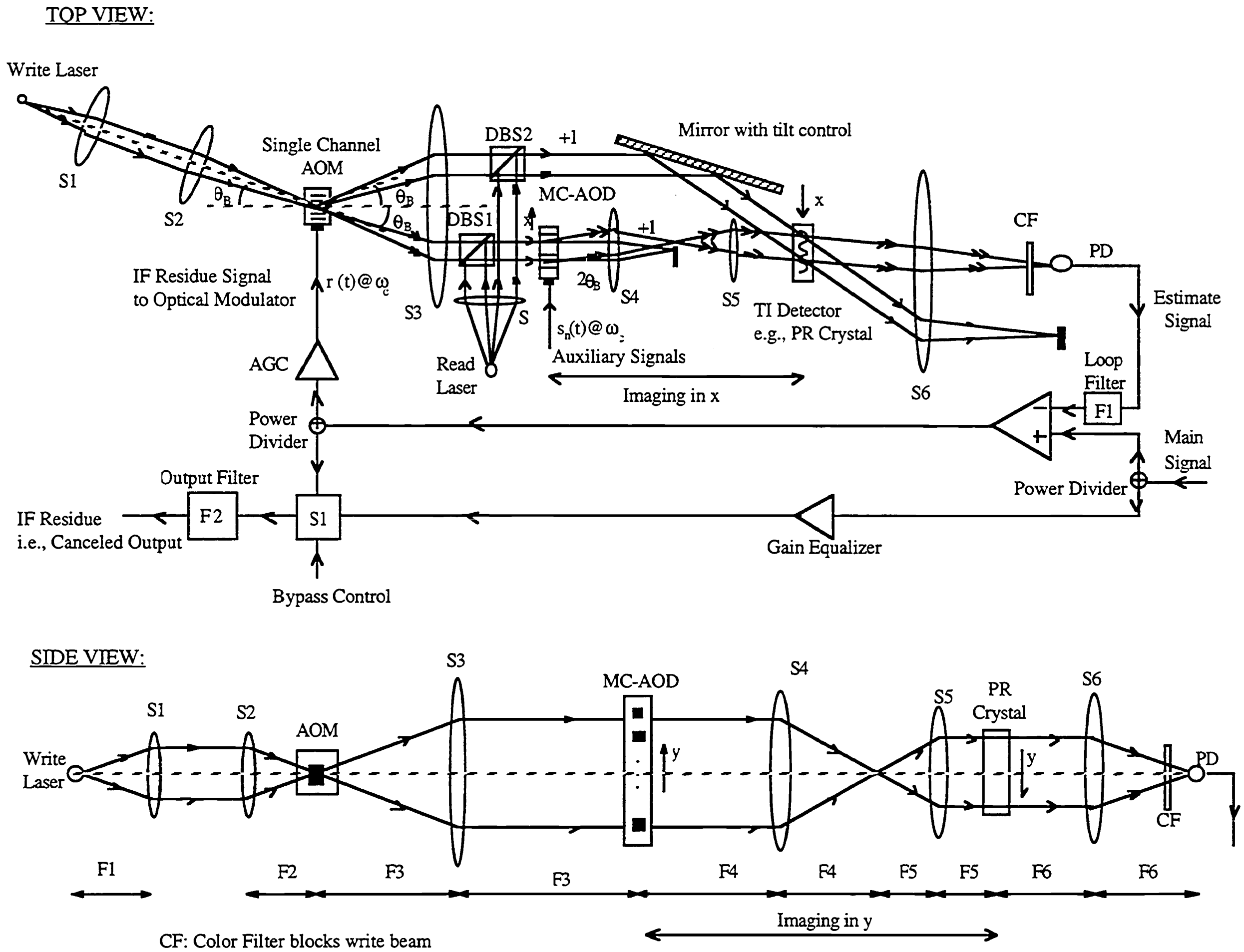
Two novel all-optical acousto-optic processor designs are introduced for antenna null steering applications. Both designs use an acousto-optic point modulator and a multi-channel acousto-optic deflector in a unique in-line arrangement to form a write/read two color system. One processor is a forward light flow optical design, while the other is a reversible light flow optical architecture. A write-only acousto-optic multichannel correlator processor design is also introduced using a counter-propagating signal correlator design. This processor also uses a time integrating detector such as a two dimensional charge coupled device or a high dynamic range photorefractive crystal for bias free correlation signal detection.

2. INTRODUCTION

Adaptive array processors are required for beam null steering in phased array antennas, with applications in radar and communication systems such as military anti-jamming radar and cellular base-station antenna applications, respectively. The adaptive array processor implements an adaptive algorithm, such as the least-mean-squares (LMS) algorithm to form a multiple sidelobe canceller (MSLC) that places nulls in the antenna beam pattern, thus suppressing both unwanted direct jammers and the multi-path reflections that deteriorate and/or corrupt the system [1]. An all-optical method for adaptive antenna processing could result in a compact, high performance processor, both for wide tunable/narrowband jammers and wide instantaneous bandwidth signaling. The key benefit of an all-optical adaptive processor is the simultaneous wide instantaneous bandwidth correlation operation of the multipath signals with the direct signals, resulting in high cancellation ratios for a moderate number (e.g., 64) of auxiliary channels. Over the years, several adaptive optical processors of a varying degree of complexity and performance have been proposed and demonstrated, both for narrowband and wideband jammers [2-12].

In this paper, we propose two novel all-optical adaptive photonic processor architectures that have a high interferometric stability almost common-path in-line design with simultaneous read and write capabilities required for all-optical processing. These adaptive processors rely on a holographic time integrating detector, e.g., a photorefractive (PR) crystal or a polmer dispersed liquid crystal material (PDLC), to provide all-optical adaptive processing. In addition, a multichannel correlator architecture is also proposed for the adaptive null-steering application, where write-only processing is implemented via a two dimensional (2-D) time integrating (TI) detector. The basic design of our proposed architectures is similar in principle to the stable in-line acousto-optic (AO) interferometer design proposed and demonstrated extensively by Riza for various signal processing applications, where both the diffracted and dc beams of the first Bragg diffraction process in the system are further fed to the processor, leading to a high overall system optical efficiency design [13-25].

3. THE AOM-AOD IN-LINE FORWARD FLOW ADAPTIVE WRITE/READ PROCESSOR



PD: High Speed Photodiode; DBS: Dichroic Beam Splitter; MC-AOD: Multichannel Acousto-optic Deflector;
AOM: Single Channel Acousto-optic (Point) Modulator; S's: Spherical Lenses, C's: Cylindrical Lenses

Fig.1 shows the proposed novel forward light flow all-optical write-read adaptive null steering processor for phased array antenna applications. This system is based on one single channel AOM (point modulator) and one MC-AOD, arranged in an in-line interferometric architecture, where the deflection of a mirror controls the spatial frequency on the TI 2-D detector.

Fig.1 shows the top and side views of the proposed forward (left-to-right) light flow system that uses a single channel acousto-optic (point) modulator (AOM) and a multi-channel acousto-optic deflector (MC-AOD), positioned in an in-line geometry. Here, as shown in Fig.1, the use of the mirror serves as spatial carrier control on the holographic TI detector, giving unique overall design flexibility. In otherwords, this design allows the generation of a variable spatial carrier on the PR crystal, such that, by mechanical rotation of the mirror (or by possible electronic deflection via a liquid crystal array device), the spatial carrier on the PR crystal can be adjusted to fully exploit the very large (e.g., 10,000) space bandwidth product available on the PR crystal.

The AOM generates a +1 order positive doppler shifted beam that is modulated by the residue signal r(t), and a undiffracted dc beam that feeds the MC-AOD. The dc beam from the MC-AOD is blocked, while its +1 order positive doppler shifted beam is modulated by the auxiliary signals $s_n(t)$. The signals driving the AO devices in this processor are centered at $\omega_c=2\pi f_c$, the AO device center frequency, which also corresponds to the intermediate frequency (IF) for the antenna processor. These AO drive signals are single-sideband (SSB) signals. Thus, the +1 order beams from the AOM and the MC-AOD have the same f_c positive doppler frequency shift, and these two write beams interfere on the PR crystal to form a volume hologram that does not have moving fringes. The automatic gain control (AGC) amplifier is used with the AOM to maintain the same relative optical power strength in the two interfering beams, as this gives a high contrast ratio grating on the PR crystal. The PR crystal material is chosen for example as Bismuth Silicon Oxide (BSO), as this material is highly sensitive to one wavelength, e.g., 514 nm, that is used for writing the high quality holograms, while another wavelength (e.g., 632 nm) is used to read the hologram without greatly erasing the hologram. Although the write and read lasers are shown in continuous wave (CW) operation for our adaptive processors, it is possible to on/off modulate these light sources for improved writing and reading of the holographic data. Furthermore, with recent advances in compact tunable laser sources and improved power laser diodes for color projection displays, a host of light sources are now available for our write/read processor application.

For the correlation weight reading process and the subsequent multi-channel convolution operation, a dichroic beam splitter (DBS) setup is used with the read laser to generate a +1 order, positive doppler shifted beam from the MC-AOD, and a zero-doppler dc reference beam via the mirror reflection set-up. Note that these two read beams almost overlap the two write beams. Thus, the read beams are optimally matched (in terms of spatial carriers) for high efficiency diffraction through the PR crystal containing the write beam hologram. Part of the +1 order read beam from the MC-AOD essentially passes uneffected (no diffraction) through the PR crystal. This read beam has the image imprint of the travelling wave auxiliary signals s_n (t-x/v) that need to be multiplied with the spatially distributed correlation weights on the PR crystal, and then summed to complete the convolution operation. On the otherhand, the diffracted zero doppler read beam from the PR crystal carrys the image imprint of the correlation weights stored on the PR crystal. A lens is used to sum these two beams and a photodiode via heterodyne detection generates the desired convolution/estimate signal riding at the ω_c IF. This signal, after AGC amplification, is fed back to the AOM, to implement the adaptive processing. A by-pass mode is also shown for the processor [12]. Fig.2 shows an alternate design to the system in Fig.1. Here, the mirror is replaced by a total internal reflection (TIR) prism and a beam splitter. This design has a higher optical loss, but more flexibility in terms of component placements and overall processor size.

TOP VIEW:

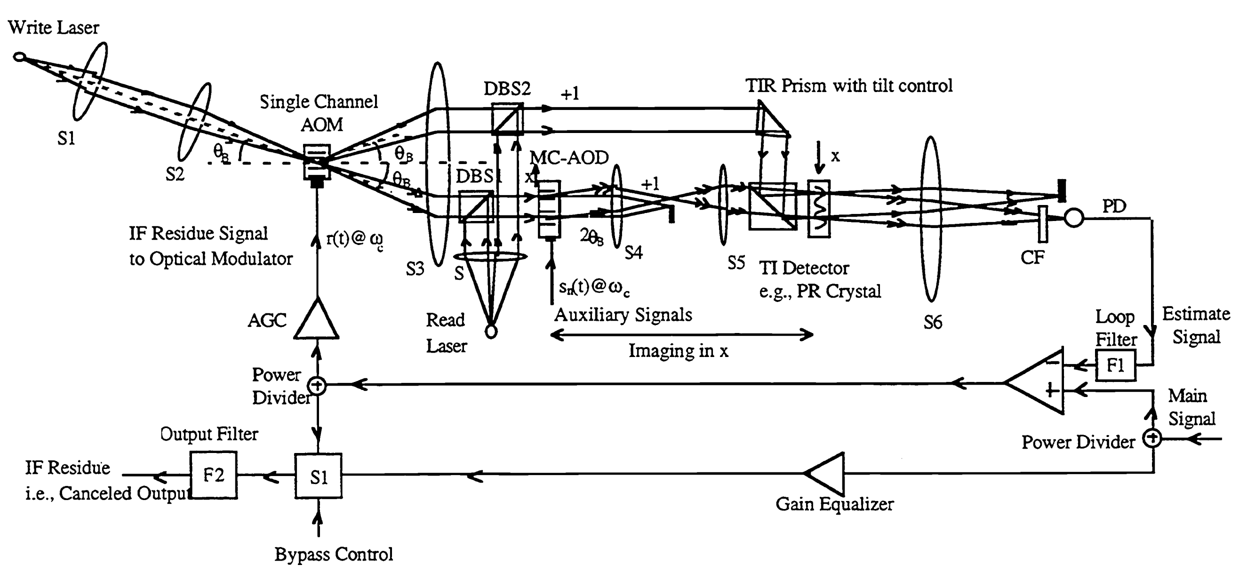


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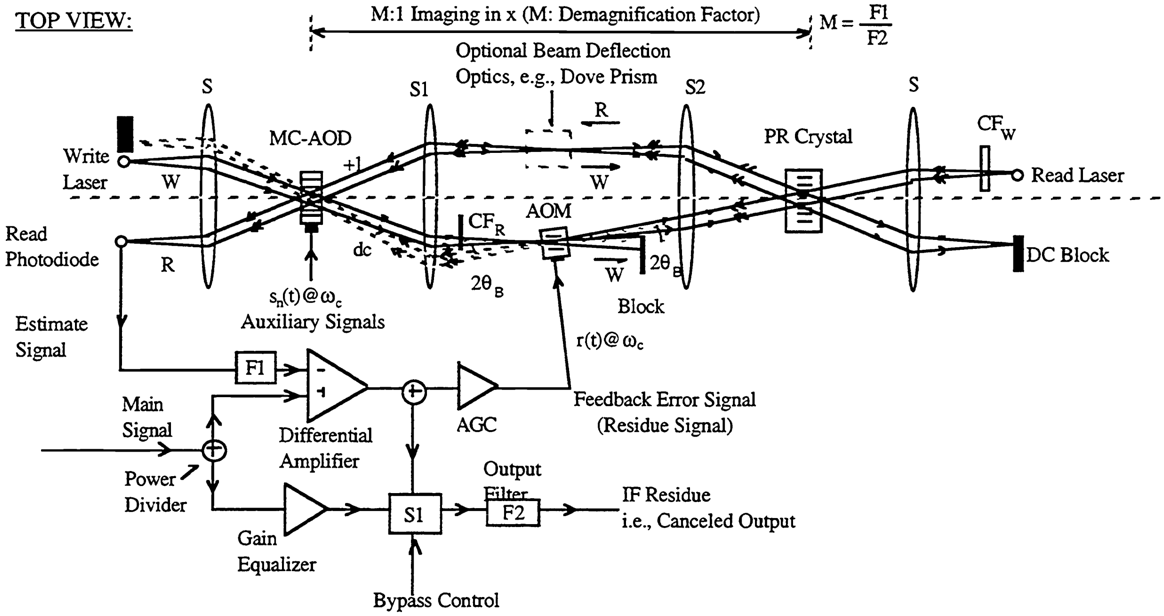
Fig.2 shows an alternative design of the proposed all-optical write-read forward flow adaptive null steering processor shown in Fig.1. Here, a TIR prism and a cube beam splitter replace the mirror in the architecture in Fig.1. This design has the potential to be smaller in size when compared to the system design in Fig.1.

4. THE AOM-AOD IN-LINE REVERSIBLE FLOW ADAPTIVE WRITE-READ ALL-OPTICAL PROCESSOR

TOP VIEW:



PARTIAL SIDE VIEW:

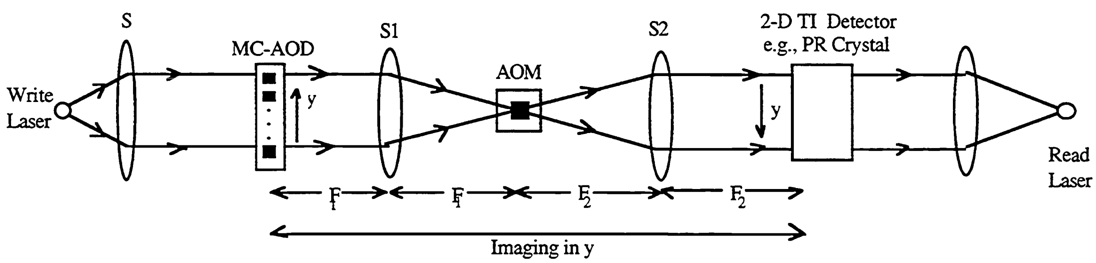


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Fig.3 shows the reversible light flow novel all-optical adaptive processor design that implements the required multi-channel correlation using the write optical beams, and the convolution operation using the reverse flow read beams.

Fig.3 shows the reversible flow novel in-line MC-AOD and single channel AOM-based all-optical adaptive architecture for null steering antenna processing. Write light flows from left-to-right while read light flows from right-to-left; hence, the reversible flow design. Light from the write laser is Bragg matched to the MC-AOD, and diffraction at the MC-AOD generates the +1 order positive doppler shifted beam and the undiffracted zero doppler dc write beam. The +1 order write beam modulated by the auxiliary signals is imaged onto the PR crystal, while the dc write beam is Bragg matched to the residue signal fed AOM positioned in the Fourier plane of the MC-AOD. Point diffraction in the AOM generates a write dc beam that is blocked, and a +1 order positive doppler shifted diffracted beam that interferes on the PR crystal with the MC-AOD +1 order positive doppler frequency modulated write beam. The TI 2-D detector, i.e., the PR crystal forms a volume hologram via the two-beam (zero relative doppler) interference that contains the correlation weight information distributed spatially. A read beam is positioned to the right of the system such that it is Bragg matched to the write volume grating that spatially modulates the correlation weight information. The read beam illumination of the volume hologram generates an undiffracted dc read beam that essentially overlaps the write +1 order beam from AOM, and a diffracted (zero doppler) read beam that is spatially modulated by the correlation weights on the PR crystal. This correlation information modulated read beam is imaged via right-to-left read light flow onto the MC-AOD. This modulated read beam essentially overlaps the write +1 order beam from the MC-AOD, and is thus also Bragg matched to the MC-AOD. Similarly, the undiffracted dc read beam from the PR crystal is Bragg matched to the AOM, and generates a +1 order diffracted beam that is blocked by the color filter CF_R , and a dc undiffracted read beam that is essentially Bragg matched to the MC-AOD. This read Bragg matching condition depends on several optical component parameters such as the S1 spherical lens focal length, the MC-AOD center frequency and acoustic velocity, and other component specifications. This Bragg matched read beam interacts with the auxiliary signals in the MC-AOD and generates a -1 order diffracted read beam that is modulated by the auxiliary signal information. This read beam has a negative doppler frequency shift of ω_c and essentially overlaps the zero doppler correlation weight modulated read beam from the PR crystal. The two beam interference and the spherical lens summing operation generates the desired residue signal at a ω_c temporal carrier via heterodyne detection at the read photo-diode. This completes the feedback convolution operation, as this residue signal is fed back to the AOM. It is important to note that Fig.3 is drawn to clearly show the different write & read beams in the system. In actuality, these beams might be much closer and overlapping, depending on the type of Bragg cells and optical components used in the system. Also note that various color and spatial block filters are used in this system. Therefore, careful alignment of components is required in this all-optical architecture.

5. THE COUNTER-PROPAGATING IN-LINE ADAPTIVE WRITE-ONLY CORRELATION PROCESSOR

Fig.4 shows the counter-propagating in-line MC-AOD and single channel AOD-based multichannel correlator architecture. This design is based on the original Riza correlator design where image inversion optics and spatial carrier control optics is used for completing the complex correlation operation [18-19]. This system uses a write laser that generates an interference pattern on the TI 2-D detector. The interference pattern stores the correlation weights generated via the simultaneous correlation operation between the auxiliary channel signals and the feedback residue signal. The TI detector can be a CCD, with the output video signal fed to a high speed electronic parallel processor that implements the convolution operation of the correlation weights with the auxiliary signals. Another option is to implement this convolution operation (i.e, weight multiply and sum) using a MC-AOD coherent optical convolver. In this case, an electronically fed 2-D grey-scale spatial light modulator (SLM) would have to be used with a MC-AOD to implement the convolution operation. If electronic mixers are used with the MC-AOD drive signals, the weight multiplication can be done electrically, eliminating the need for the 2-D SLM. It would be beneficial to use the same MC-AOD for the correlation and convolution operations, and this would be possible, given certain modifications to the processor shown in Fig.4. Also note that the TI 2-D detector can be a PR crystal, and the correlation weights can be read using a separate read beam. This technique creates a high dynamic range TI detector, as the uniform bias light level does not eat up the dynamic range of the TI detector, and the useful correlation information can be read bias-free with an optical-to-electrical detector such as a CCD.

Unlike the other adaptive processors introduced earlier in the paper, this counter-propagating architecture generates a factor of two time and space compression in the correlation plane (see Fig.5). Thus, before implementing the multichannel convolution operation, the electronic post-processor must choose the corrected (or time expanded by factor of 2) correlation weights. Thus, this multichannel correlator architecture does have its complexities; although, it does use the full apertures of the AODs to provide high light throughput and twice the correlation signal processing window compared to our previous designs using an AOM.

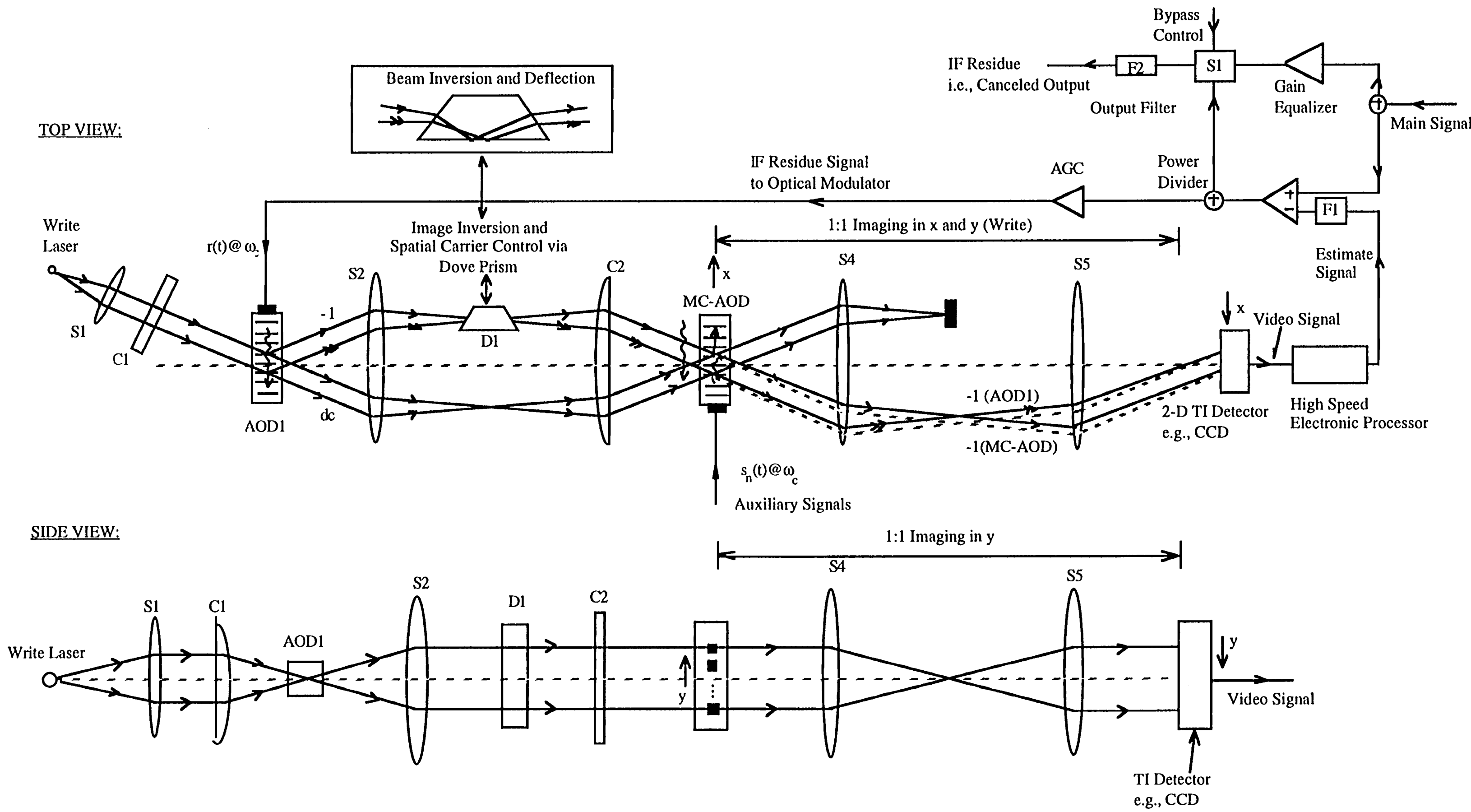

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Fig.4 shows a novel optical adaptive processor design that implements the required multi-channel correlation using a two AOD device counter-propagating geometry. The multi-channel convolution is shown as implemented via electronic means, although, the same optical processor, using a read beam and some additional optics, can implement the convolution. This design results in a doubling of the correlation/weight processing time window along with improved system optical efficiency. Nevertheless, the system does add considerable optical design complexity in terms of implementing an all-optical write-read processor.

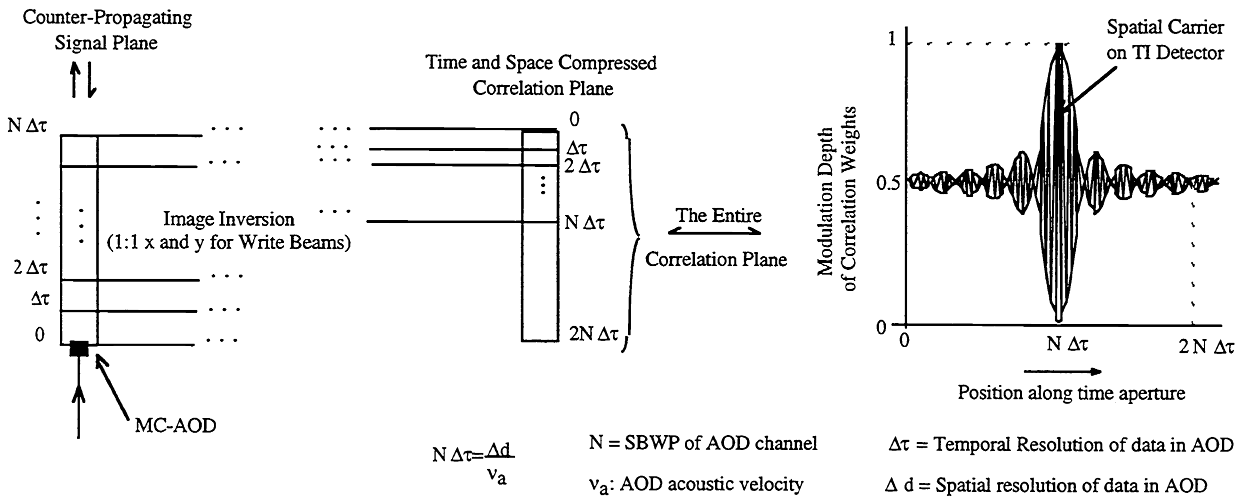

Fig.5 shows the results of an AOD-based counter-propagating signal geometry acousto-optically processed correlation output, where the output correlation plane undergoes a factor of two expansion in time, and the output correlation signal is a double-sided function.

6. CONCLUSION

This paper has introduced a variety of AO processors for phased array adaptive processing. In particular, two all-optical write-read processors are introduced that implement both the multi-channel complex correlation operation and the feedback multi-channel complex convolution operation (multiply and sum) in a single optical architecture. A write-only processor design is also introduced that implements the multi-channel complex correlation operation required for adaptive array processing. Here, the feedback multi-channel complex convolution operation is implemented electronically, although, optical convolution is also possible within the correlation architecture, given certain design modifications. The choice of the appropriate photonic adaptive array processor design depends on the system application, e.g., radar or mobile communications, and its requirements. Future work relates to the experimental demonstration of these systems.

7. REFERENCES

[1] B. Widrow, P. Mantey, L. Griffiths, and B. Goode, "Adaptive antenna systems," *Proc. IEEE*, Vol.25, pp.2143-2159, 1967.

[2] W. A. Penn, "Acousto-optic adaptive signal canceller," *Proc. ICALEO*, Laser Institute of America, pp.9-17, 1982.

[3] A. VanderLugt, "Adaptive optical processor," *Applied Optics*, Vol.21, No.22, pp.4005-4011, 1982.

[4] J. F. Rhodes, "Adaptive filter with a time domain implementation using correlation cancellation loops," *Applied Optics*, Vol.22, No.2, pp.282-287, 1983.

[5] D. Psaltis and J. H. Hong , "Adaptive acousto-optic filter," *Applied Optics*, Vol.23, No.19, pp.3475-3481, 1984.

[6] J. Cohen, "Optical adaptive linear predictors," *Applied Optics*, Vol.24, pp.4247-4259, 1985.

[7] J. Hong, S. Hudson, J. Yu, and D. Psaltis, "Photorefractive crystals as adaptive elements in acousto-optic filters," *SPIE Proc.* Vol.789, 1987.

[8] C. W. Carroll and B. V. K. Vijaya Kumar, "Application of optical processing to adaptive phased array radar," *SPIE Proc.*, Vol. 936, pp.142-151, 1988.

[9] R. M. Montgomery and M. R. Lange, "Photorefractive adaptive filter structure with 40 dB interference rejection," Applied Optics, Vol.30, No.20, pp.2844-2849, July 1991.

[10] D. B. Friedman, D. P. Dwyer, and R. M. Iodice, "Acousto-optic null steering processor (AONSP)," *SPIE Proc.*, Vol. 1958, pp.83-87, Orlando, Florida, 1993.

[11] J. H. Hong and T. Y. Chang, "Adaptive signal processing with photorefractive systems," *SPIE Proc.*, Vol. 2489, pp.36-44, Orlando, Florida, 1995.
[12] R. M. Iodice and P. H. Ruterbusch, "Acousto-optic null steering processor (AONSP) hardware performance summary," *SPIE Proc.*, Vol. 2489, pp.45-64, Orlando, Florida, 1995.
[13] N. A. Riza, "Novel acousto-optic systems for spectrum analysis and phased array radar signal processing," Ph.D dissertation, (California Institute of Technology, Pasadena, Calif., 1989) in *University Micofilms*, Ann Arbor, MI.
[14] N. A. Riza, "Acousto-optic architectures for multi-dimensional phased array antenna processing," *SPIE Proc.,* Vol. 1476, pp.144-156, 1991.
[15] N. A. Riza and D. Psaltis, "Acousto-optic signal processors for transmission and reception of phased array antenna signals," *Applied Optics*, Vol.30, no.23, pp.3294-3303, 1991.
[16] N. A. Riza, "Liquid crystal-based optical control of phased array antennas," *IEEE /OSA Journal of Lightwave Tech.*, Vol.10, No.12, pp. 1974-1984, Dec., 1992.
[17] N. A. Riza, "Optically efficient interferometric acousto-optic architecture for spectrum analysis," *Applied Optics*, Vol.31, No.17, pp.3194-3196, June 10, 1992.
[18] N.A. Riza, "The in-line acoustooptic interferometer as a correlator and spectrum analyzer," *SPIE Conf.*, Vol. 2026, pp.130-141, 1993.
[19] N. A. Riza, "In-line interferometric time integrating acoustooptic correlator,"*Applied Optics*, Vol.33, No.14, pp.3060-3069, May 10, 1994.
[20] N. A. Riza, "Acousto-optic liquid crystal analog beamfomer for phased array antennas,"*Applied Optics* , Vol. 33, No.17, pp.3712-3724, June 10, 1994.
[21] N. A. Riza, "Novel space/time integrating acoustooptic architectures for radar signal processing," *SPIE Proc.* Vol. 2155, Jan., 1994.
[22] N. A. Riza, "Space Integrating Interferometric Acousto-optic Convolver," *IEEE Photonic Technology Letters*, Vol.7, No.3, pp. 339-341, 1995.
[23] N. A. Riza, "Optical Beamforming for Ultrasonic Phased Arrays," *IEEE LEOS Ann. Meeting Proc.*, EOS4.1, San Francisco., Nov., 1995.
[24] N. A. Riza and M. M. K. Howlader, "Acousto-optic System for the Generation and Control of Tunable Low Frequency Signals," *Optical Engineering*, Vol. 35, No.4, April, 1996.
[25] N. A. Riza and M. M. K. Howlader, " Photonic processor for in-phase and quadrature array signal processing," *SPIE Proc.*, Vol. 2754, No.06, Orlando, Florida, April, 1996.