Flexible Beamformer and Remoting Head for Optically Controlled Phased Array Antennas

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Abstract — **Unique photonic beamformer and remoting head for array antennas in broadcast mode wireless communication is proposed enabling for the first time, flexible antenna array upgrades via software and flexible front-head attachments leading to user defined changes in number of antenna elements and carrier frequency. Initial experimental results are described.**

I. Introduction

With the current explosion in wireless communication services, future communication antennas will utilize electronically scanned non-mechanical smart antennas similar to advanced military Phased Array Antennas (PAAs). Previously reported PAA designs utilized pixelated, electrically addressed, liquid crystal (LC) devices to generate radio frequency (RF) beam steering information [1]. In such systems, number and size of individual LC pixels dictated the size of the optical head and in turn the number of elements in the antenna array [2]. Such an approach poses strict limitations on the antenna upgradability in terms of number of elements in the antenna array. An effort to change the number of elements in the antenna array would require replacement of an existing LC device in the beamformer with the one having proper pixels. This will require a new optical head, not to mention the changes to the beamformer controller system in order to match the new LC device size. Furthermore, pixelation causes diffraction with light from one pixel leaking into a detector or fiber collimator placed in front of an adjacent pixel, consequently sending wrong phase information to the corresponding antenna element.

It would be highly beneficial to develop a photonic beamforming approach where all aspects of the antenna control are flexible; namely, choice of antenna carrier, number of RF phase shifters in beamformer, and number and spatial distribution of the light sampling elements in the optical-to-RF interface remoting head. Recently we proposed such a unique photonic beamforming concept [3]. In this paper, the flexible beamforming concept is further explored and basic experimental results are validated. With the proposed design, a PAA system will become upgradeable without requiring major hardware changes and thus can expedite the use of smart PAAs in the wireless arena.

II. Flexible Beamforming Architecture

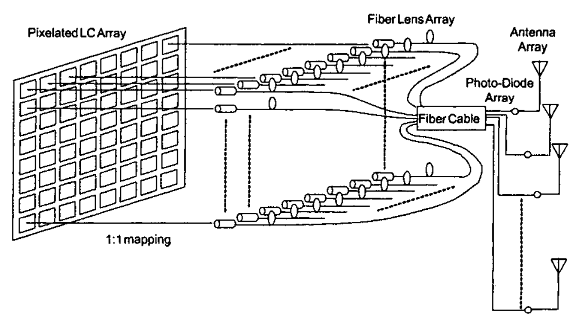

Fig. 1. Traditional interface between a pixelated beamformer and an antenna front-end showing the fixed 1:1 mapping between phase shifter array and antenna array. Example shows a transmissive LC pixelated array device. Any other type of pixelated device can also be accommodated in this interface.

Fig. 1 shows the prior art generalized 1:1 mapping between a pixelated spatial light modulator (SLM)-based beamformer and the antenna array front-end. This approach to beamforming causes several PAA system limitations that includes (a) fixing the number of antenna elements, (b) system loss and inter-fiber crosstalk due to pixel-based diffraction, (c) no system flexibility via fixed precision area mapping between pixel array and fiber-lens array, and (d) zero tolerance to fiber array fabrication errors and assembly misalignments.

* Also with Nuonics, Inc., Orlando, FL (www.nuonics.com)

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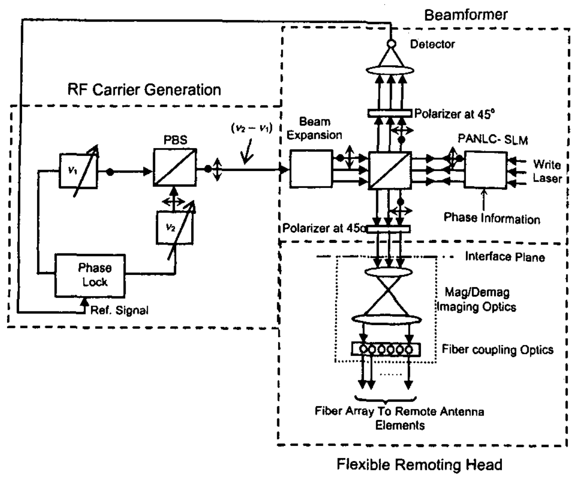


Fig. 2. Block Diagram of the Proposed Flexible Photonic Beamforming Concept for PAAs.

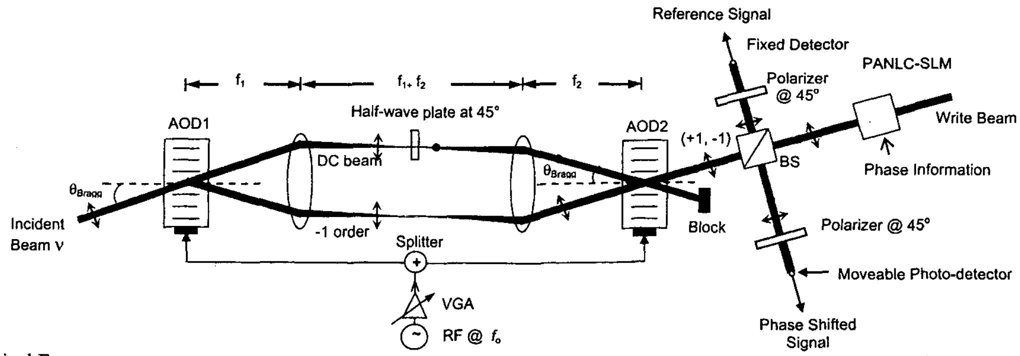
Fig. 2 shows a schematic of our proposed flexible beamforming approach involving three flexible sub-systems. The carrier generation system based on well known heterodyne mixing is flexible as tuning of the phase-locked lasers can generate any desired RF from sub-Hertz to 100 GHz. As shown in Fig. 2, this design setup utilizes two laser sources with slightly different frequencies that are phase locked with each other. The difference of the two optical frequencies serves as the RF frequency for the antenna array. A beam splitter (BS) is used to split the incoming *s* and *p* polarized collinear light beams into two parts. Part of light from the BS is used to generate the reference signal (top) for phase-locking whereas the rest of light goes straight to the beamforming sub-system. For simplicity, the analog/digital data modulation scheme in this subsystem is not shown.

As an example, the design in Fig. 2 utilizes LC technology for realizing the flexible beamformer sub-system. Specifically, an optically addressed, non-pixelated, reflective Parallel Aligned Nematic Liquid Crystal (PANLC) SLM is used as the film-like non-pixelated flexible phase shifter array to realize the desired flexible photonic beamformer. This SLM write light carries the required RF phase information image that is embedded via a high space bandwidth product (e.g., half a million pixels) electrically addressed, amplitude mode pixelated, transmissive LC SLM or an optically generated image former. The reflective non-pixelated SLM structure is critical to our approach in realizing a flexible interface between the RF front-end and the photonic beamformer. Because the SLM is film-like, essentially any desired spatial phase shifter structure can be generated via software leading to a truly flexible interface between the antenna elements and the beamformer. With reference to the PANLC-SLM in Fig. 2, one of the two incident polarizations on the read side of the SLM picks up the desired phase information written from the write side of the SLM. The two orthogonal linear polarizations then pass through a 45° polarizer before they connect to the antenna interface sub-system eventually falling on the photo-detector array that generates the desired RF phase shifted signals for the antenna array.

Hence the third flexible subsystem is the antenna interface sub-system that is antenna dependent. This plug-in plug-out subsystem contains an imaging system that matches and maps the antenna fiber-array to the read SLM face. In other words, whenever a new antenna array requires photonic beamforming, this antenna's optical interface-head subsystem is plugged into the generic fixed beamformer sub-system, and simply via software control, antenna steering is achieved. In short, the proposed three sub-systems acting together form the overall flexible beamforming architecture.

III. EXPERIMENTAL RESULTS

Fig. 3 shows the implemented experiment that uses a *p* polarized 532 nm laser read beam, two Acousto-Optic Deflectors (AODs), a PANLC-SLM from Hamamatsu, and other beamforming optics to realize a proof-of-concept demonstration. The two AODs are fed with 70 MHz RF signals and serve the purpose of splitting and recombining the optical beam(s) forming a coherent high stability heterodyne interferometer. This AOD-based system provides a setup to generate a tunable RF antenna carrier signal at the eventual photo-diode output where the heterodyne detected RF equals twice the AOD drive frequency; in this case, 140 MHz. AOD1 deflects the incident laser beam into two parts: the undiffracted DC beam and the -1 order. These two beams are then made incident upon the AOD2 with Bragg-matching. The DC beam is *s* polarized because of the half-wave plate in its path. The DC beam now undergoes a +1 diffraction. The two diffractions from the two AODs are now collinear but orthogonally polarized. The two collinear laser beams enter the second sub-system where they pick-up the RF phase information from the PANLC-SLM. A photo-detector on a translational stage is used to simulate the flexible interface head or third sub-system in the overall PAA controller. This detector positioned in two dimensional space is tracked via software changes on the location of the RF phase map embedded on to the



ν: Optical Frequency;
f_i: Focal Length of ith Lens;
AOD: Acousto-optic Deflector;
VGA: variable Gain Amplifier.

Fig. 3. Experimental setup of the proposed flexible beamforming concept implemented using acousto-optics and nematic LC technology.

PANLC-SLM. Fig. 4 shows the RF signals generated from the fixed reference photo-detector and the movable output port detector for a given output port photo-detector location. These oscilloscope traces clearly indicate the ability of our proposed controller to provide desired phase shifts for PAAs with any front-end interface setup. Fig. 4(a) shows the case when there is no phase shift with respect to the reference waveform while Fig. 4(c) displays a relative phase shift of π radians. Fig. 5 shows the measured RF phase shift data provided by the flexible beamformer, showing near 2π phase shift control.

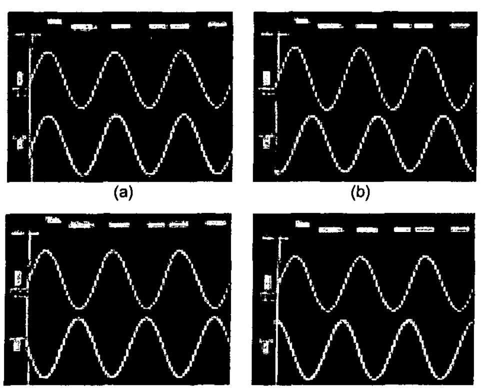


Fig. 4. 140 MHz oscilloscope traces from the Flexible Beamformer: (a) in-phase, (b) 90°, (c) 180° and (d) 270° out of phase signals at the detectors. The top trace is the reference waveform whereas the bottom one is the beamformer phase-shifted signal.

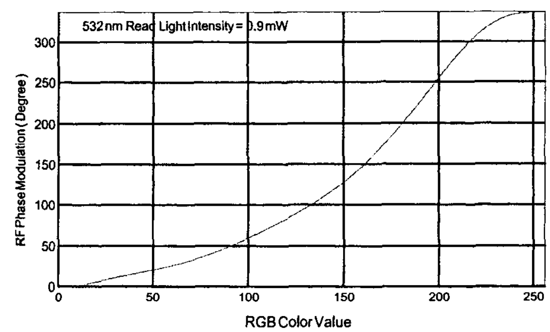


Fig. 5. The measured RF phase shift data provided by the flexible beamformer, showing near 2π phase shift control versus RGB color value of gray-scale image written on the write SLM of the Hamamatsu device. 0: Black state, 255: White/Transparent state.

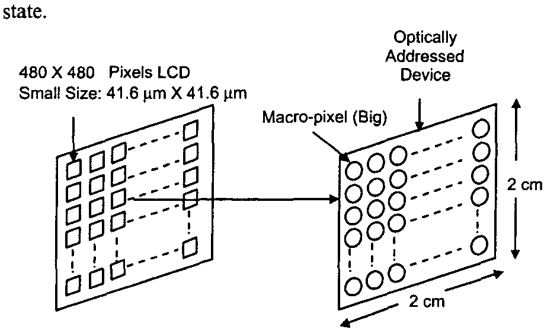


Fig. 6. The very high count of 230,400 pixels of the write amplitude-mode LC device in the Hamamatsu LC device module gives "Flexible Beamforming" additional powers such as high resolution phase averaging and overall system fault-tolerance via the macro-pixel per RF phase shifter concept.

An important point to note, as also shown in Fig. 6, is the high space bandwidth product (SBWP) benefits of the Hamamatsu device. Specifically, the image generation LC device has a very large 480 x 480 = 230,400 pixels, with each pixel being a small 41.6 micron x 41.6 micron. The active area of the optically addressed square area device is 2 cm x 2 cm. This area is used for generating the desired spatial distribution N RF phase shifters for N elements of the PAA. Typically, N is from 50 to 5000. Since we have 230,400 pixels and much fewer antenna elements, as little as 46 pixels and as many as 4,608 LC pixels are required to create a phase shifter site on the SLM for 5000 to 50 element PAA, respectively. Hence, a macro-pixel effect is used to realize the RF phase shifters via optical means, giving greater flexibility to RF phase control via the prior art single pixel phase control approach. This high LC SLM SBWP adds to the overall phase control power of the proposed flexible beamforming approach, in addition giving it a unique fault-tolerance feature to individual pixel failure.

IV. Conclusion

In conclusion, we have proposed and experimentally demonstrated the basics of the concept of flexible photonic beamforming. The system proposed in Fig. 1 is particularly appropriate for broadcast mode RF phase-steered PAAs. The demonstrated LC device-based beam controller has the capability to provide near 2π RF phase shifts desired for narrowband beamforming. The experimental results attest to the functionality and applicability of our system in smart antennas for efficient wireless communication. Future work relates to the optimization of the controller hardware. The flexible beamforming concept can be extended to true time delay systems and other SLM device technologies.

Acknowledgement

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