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Advanced Novel Photonic Instrumentation for Adaptive and Interferometric Astronomy

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ABSTRACT

New advanced photonic instrumentation previously developed for photonically controlled phased array antenna/radar work, is proposed for astronomical applications. The proposed adaptive optics approach is to use these remotely located photonic phase, time delay, and amplitude control modules for wavefront correction and optical beamforming for astronomical applications, particularly where fiber remoting can lead to larger observation apertures and/or signal processing gains. Scenarios using our photonic instrumentation such as solar wind sensing using radio frequency antenna arrays and fiber-linked optical telescope arrays are highlighted.

2. INTRODUCTION

Since the beginning of astronomical observations in early civilizations, as in ancient Greece over 2.5 millenia ago, astronomers have strived for better "seeing" instrumentation for making their discoveries, and verifying theories about the universe. Initial astronomical observations evolved with bigger and higher optical quality single aperture optical/visible telescopes pointed towards the skies over hills or clear atmospheric regions. Even today, the modern astronomer desires to build, as large as technologically possible, a light collecting aperture that would produce the higher "seeing" resolution. The 1930's unexpectedly brought the new age of radio astronomy where radio waves instead of visible light energy was detected to indicate presence of remote heavenly objects such as pulsars and radio galaxies. The instrument for detecting radio waves was the radio antenna that was originally developed and used during the Second World War for military communication and radar applications in the high frequency (e.g., 30 Mhz) to microwave part (e.g., < 3 Ghz) of the electromagnetic spectrum. Today, because of steady

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advances in detection instrumentation over the last 25 years that were largely developed by the aerospace and medical industry, astronomers have state-of-the-art instrumentation for detecting a wide variety of remote signals such as gamma rays, X-rays, and visible, near infrared, far infrared, and millimeter wave radiation.

Today's astronomers have devised clever techniques to overcome key limitations and problems with earlier instrumentation, such as limitations due to the large physical size and inertia limited gravity-based warping of large mirrors, and the atmospheric turbulence effects that limit image quality for terrestrial-based remote sensing. Adaptive optics and interferometry have emerged as the key solutions for making diffraction limited large (e.g., 8 meter diameter) telescopes, and for synthesizing very large aperture, high angular resolution and gain, viewing systems via the use of an array of telescopes. The key questions to ask are how many independent deformable mirror segments are required in an adaptive optical system to compensate for atmospheric turbulence, and what is the minimum size of these visible mirrors such that they cover the entire space bandwidth product of the large aperture optical telescope. The answer, depending on the telescope, wavelength, and application could mean a 1000 or more independently controlled mirrors that might have to be mechanically moved over several tens of 2π radian optical cycles in less than a millisecond. Even with these advanced adaptive optical systems, single telescopes will be limited to around 10 milliarcseconds angular resolution; nevertheless, at least a factor of 10 improvement over seeing-limited telescopes [1]. For a factor of 100 or more improvement in angular resolution over adaptive optical systems, baseline interferometry will be used, and a number of very long baseline (e.g., from tens of meters between antenna spacing to 1000's of km) systems are now under development. To get better performance from these interferometer arrays, it is well known from phased array radar theory that the greater the number of elements in the array, the higher the degrees of freedom in the signal space for manipulation of the resultant transmit/receive beam pattern for achieving higher gain, scan resolution, and scan angle/pattern control for lower sidelobes. Because of the large separation between the individual antennas/telescopes in baseline arrays, most arrays active today or being planned for the future have only around 10 individual elements in the array. In reality, it would be beneficial to the astronomer to have a higher count (e.g., 100) for the number of elements in the base-line interferometer array.

In this paper, we introduce, perhaps for the first time, the use of new advanced photonic instrumentation related to photonically controlled phased array antenna/radar work, that can be used for remote adaptive optical control applications such as for atmospheric turbulence

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correction as well as physical aperture manufacturing defect correction in a single large telescope. In addition, our advanced remotely located photonic phase, time delay, and amplitude control modules can be used for baseline interferometer arrays. The near term application areas for this new photonic instrumentation include radio astronomy, and visible and infrared astronomy. These systems can be terrestrial, airborne, or space-based.

The basic motivation for the ideas proposed in this paper stem from the author's work over the last decade on photonic control systems for radio frequency (rf) and microwave-band phased array antennas [2-10]. Much like the impetus received by radio astronomers in the 1940's due to rapid developments by radar engineers in high performance electrical transmitters and receivers, the author is proposing his recent innovations in photonic control modules for rf and microwave phased array antennas for use as control instrumentation in adaptive and array-based radio, visible, and infrared astronomy systems for the next millenium. These photonic control modules are multi-channel, compact, robust, reversible, potentially low cost, wide tunable and instantaneous bandwidth sub-systems, with switching speeds in the millisecond to microsecond range. This paper will highlight how these photonic modules can be used for high resolution astronomical instrumentation such as > 50 element adaptive arrays with remotely implemented adaptive optical control per antenna/telescope.

3. RADIO FREQUENCY ANTENNA ARRAY FOR RADIO ASTRONOMY

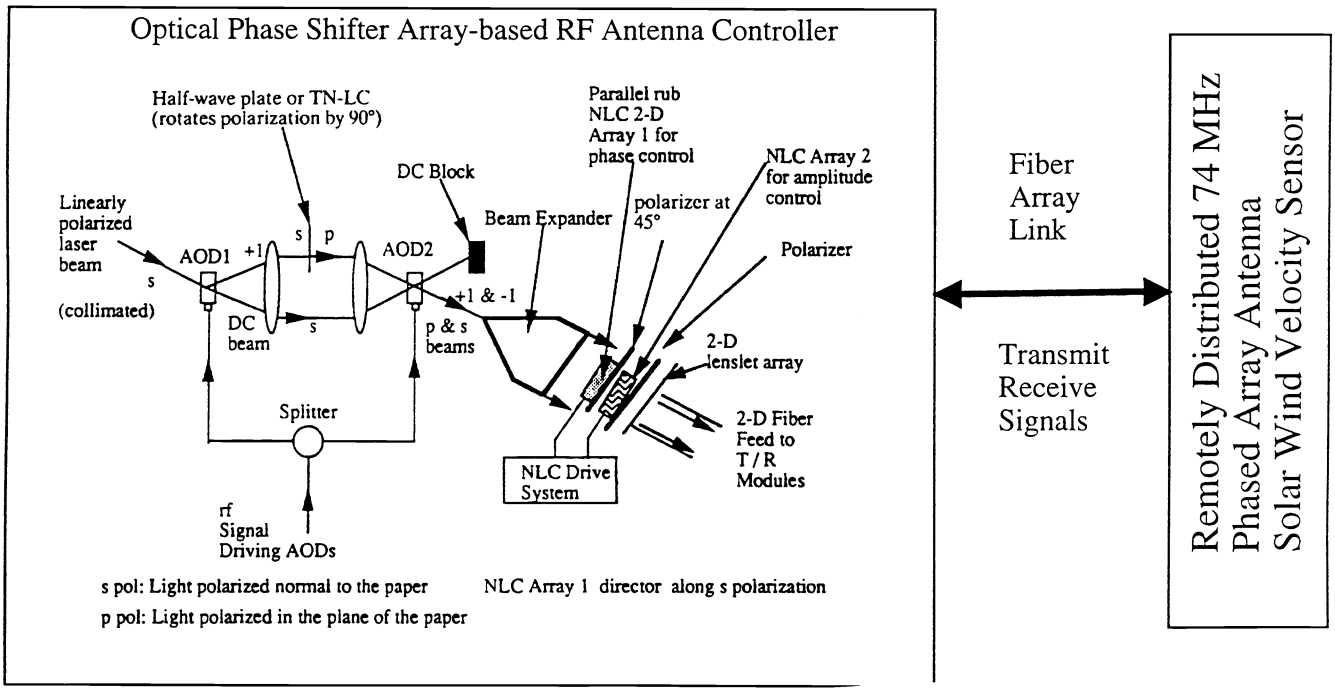
Recently, a 74 Mhz electronically controlled phased array antenna has been proposed and tested for the radio astronomy application of solar wind velocity detection [11]. . Typical specifications for such a solar wind sensor antenna array include 48 by 70 antenna elements, a 2 Mhz bandwidth, integration or dwell times > 400 s and even up-to 30 minutes, and rf phase errors of < 1 degree with 7 bits of rf phase control. These performance numbers can be well handled by our previously demonstrated acousto-optic (AO) liquid crystal (LC) phase-based photonic controller for rf phased array antennas [3]. This photonic controller can be fiber-linked to the remote solar wind sensor rf antenna array as shown in Fig.1. The details of the photonic controller are well described in ref.3, and hence are not discussed in this paper. For a 74 Mhz rf carrier, the Bragg cells in the photonic controller are fed by 37 Mhz rf signals. Receive array rf processing using this photonic controller is based on local oscillator signal set mixing to generate an intermediate frequency (IF) signal signal for final electronic summation. This photonic controller provides key features that can benefit astronomical applications. These include potentially low overall system cost, essentially hardware insensitive frequency bands of operation, low total overhead control power via the use of two stamp size nematic LC devices,

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and fiber remoting. Note that in a similar fashion, distributed radio antennas can be fiber-linked to the photonic controller for forming very large adaptive base-line radio telescopes.

Astronomical Scenario 1
Using The Adaptive Phase-based Photonic Instrumentation

Photonically Controlled 74 MHz RF Phased Array Antenna for Solar Wind Velocity Detection



NLC-based optical control system using the in-line AO interferometer for beat-frequency signal generation: TN-LC, twisted-nematic liquid crystal; T/R, transmit and receive.

Fig.1 Our novel optical phase shifter array system that can be used to control fiber-linked RF antenna arrays used for solar wind sensing.

4. VISIBLE AND INFRARED ADAPTIVE OPTICAL ASTRONOMY USING NOVEL THREE DIMENSIONAL POLARIZATION SWITCHED OPTICAL DELAY LINES

Adaptive optics has proved extremely valuable for astronomers viewing dim stars at great distances [12]. Wavefront corrections have been made by mechanical motion of mirrors, also called deformable mirrors. More recently, the use of fiber-optics has become prominent for

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astronomical applications [13]. In particular, there is a need for a high performance variable time delay optical delay line for various astronomical applications such as Fourier transform spectrometry (FTS), double Fourier interferometry (DFI), and single-mode fiber-linked telescope arrays [14].

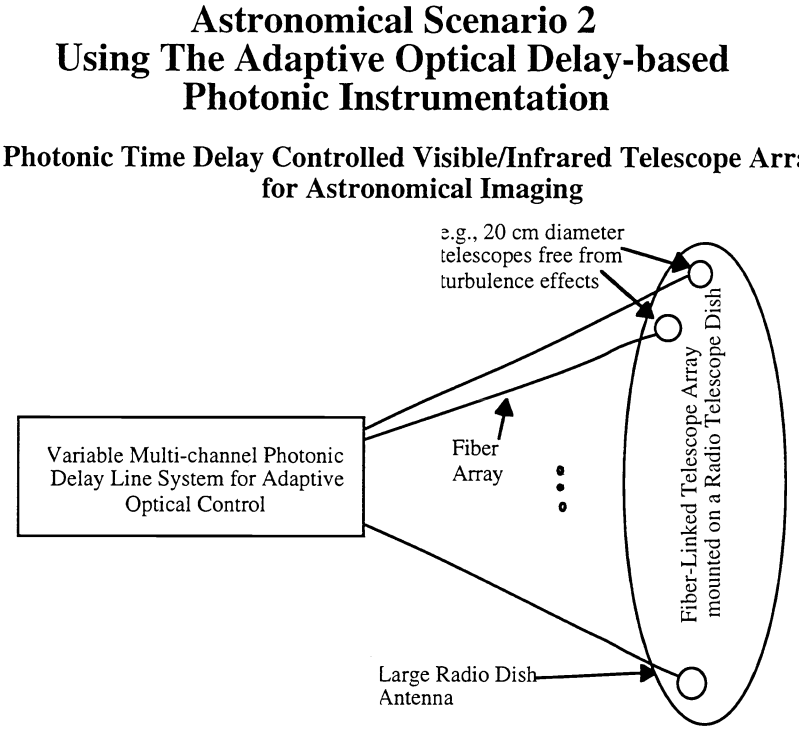


Fig.2 Our novel photonic delay lines can be used with fiber-linked telescope arrays.

Recently, a fiber-based variable optical delay line has been proposed for astronomical applications where tunable fiber coupler-based fiber-optics has been suggested as the preferred optical switching, routing, interconnection, and delay technology [15]. On the contrary, the author has developed various types of free-space, solid-optics, and fiber-based photonic delay lines that rely on three dimensional (3-D) interconnection optics and two dimensional (2-D) thin-film planar switching planes [4-6,9-10]. These 3-D photonic delay lines can be used for astronomical applications where high channel count (e.g., > 50) array signal processing is required, such as the scenario shown in Fig.2. Our typical novel variable delay line for astronomical applications is shown in Fig.3, where the optical delays are achieved via fiber, solid-optics, and free-space delays. Because our optical beam control modules use 3-D optics, it is easily possible to achieve high channel densities, e.g., > 1000 channels in a 2.5 cm by 2.5 cm delay path cross-section. Furthermore, a wide range of time delays are possible using either free-space, solid-optics, and/or fiber-based designs. N-bit discrete control is possible using the

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cascaded on/off switched delay line designs, and continuous high resolution delays is possible using electrically programmed birefringent-mode nematic liquid crystal devices.

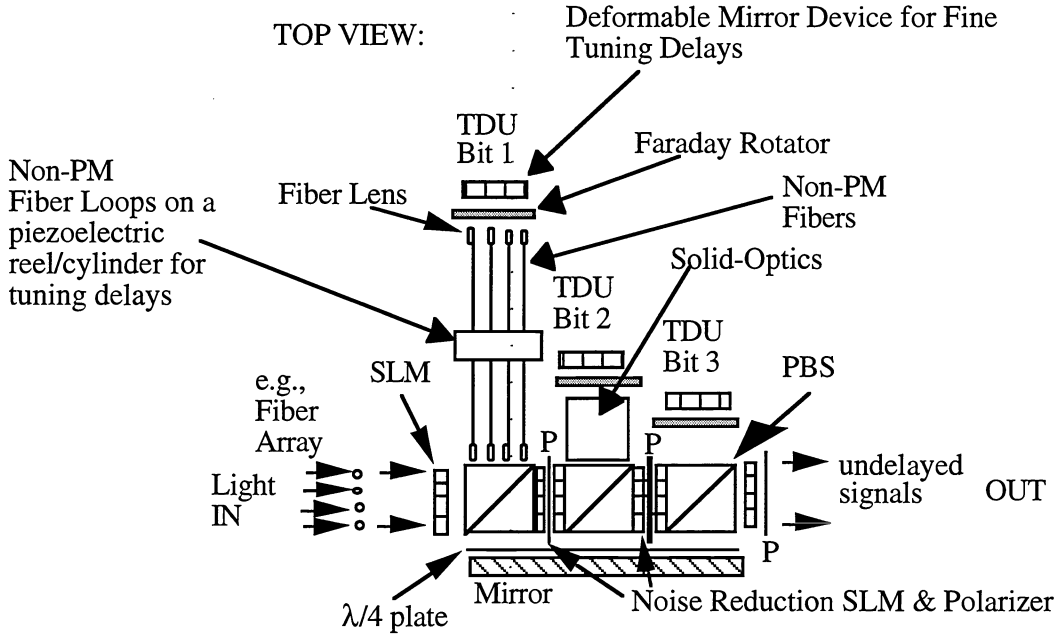


Fig.3 shows the top view of the proposed variable and switched high resolution and larger time delay N-bit M channel optical delay line. Fine time delay control is achieved via piezoelectrically actuated mirror piston-type motion and via fiber stretching on piezoelectric cylinders.

The 3-D multichannel photonic delay line shown in Fig.3 is unique in the sense that it provides both multichannel high resolution variable time delay control and the larger multichannel switched time delay control. Continuous high resolution delays are provided using piezoelectrically actuated mirror motion in the reflective optical design (e.g., using piston-type electrically programmable deformable mirror devices) and fiber-stretching using piezoelectric reels/cylinders and appropriate fiber wrapping methods. Details relating to our 3-D photonic photonic delay lines such as polarization effects, optical loss, switching speed, crosstalk, etc, are addressed in our references.

5.CONCLUSION

The purpose of this paper is to link the author's photonic control work for phased array radars to applications in astronomy. Two typical scenarios are highlighted using the author's novel photonic instrumentation. Much like the 1940's and 50's electronically controlled radar work, today's astronomers can also benefit from the author's work in photonically controlled radars. A

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novel multichannel optical delay line with both multichannel variable high resolution and multichannel switched large time delay control is introduced for astronomical applications. Future work involves the author's collaboration with an astronomer for a possible prototype system using the proposed high resolution large delay multichannel photonic delay line. Details of the author's work in photonically controlled radars is provided in the reference list, and hence not repeated in this paper.

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