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Fault-Tolerant Multi-Beam Photonic Beamforming for Wideband Array Antennas

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1. INTRODUCTION

Advanced military systems such as wide instantaneous bandwidth phased array radars and electronic warfare (EW) receivers are challenging the present capabilities of both electronic and optical signal processing hardware. As bandwidth transparency of hardware has become a much desired attribute for system designers such as high spatial resolution tracking of missiles, optics has become a key technology for the implementation of these wide instantaneous bandwidth processing functions [1]. Recently, the availability of wide bandwidth (e.g., DC-20 Ghz) and high dynamic range (> 100 dB) analog fiber-optic links has fueled the push towards next generation wideband array signal processors using these input/output links. It is envisioned that these wideband optical beamformers for advanced radars will be used in combination with electronic analog-to-digital sampling-based beamformers to meet the diverse needs of military scenarios.

The critical components to implement array radar beamforming is the fiber-optic variable optical delay line (VODL) and the fiber-optic variable optical attenuator (VOA). A phased array antenna beamformer is a multi-point to multipoint configuration where a series of independently controlled VODLs and VOAs provide the delay and gain values, respectively, for radar beam steering and shape controls. The requirements for these VODLs and VOAs in terms of insertion loss, time delay range, time delay resolution, gain control dynamic range, gain resolution, and switching speed can vary based on the radar function. On the contrary, the VODL and VOA requirements on cost, performance upgradeability, scalabilty, size and weight, temperature and vibration robustness, and most importantly, fault-tolerance, do not vary much and are extremely stringent for platforms. In short, these parameters should not be compromised, if at all possible.

Unfortunately, todays VODLs and VOAs are highly lacking in these mentioned parameters. These issues in todays VODLs and VOAs can mainly be blamed on their singular mode of design and operation where no fault-tolerance and flexibility exists either in the architecture or device hardware. Thus to solve these key problems, a design paradigm change is required. We propose this new paradigm for fiber-optic VODLs and VOAs that are combined in a unique flexible beamformer module that can easily be reconfigured and upgraded based on radar type and requirements.

Generation of multiple simultaneous radar beams requires multiple independent beamformers. For large antennas with many (e.g., 100) beams means a large amount of independently processed signaling channels are required, adding a massive cost, weight, and size load on the antenna control system. Hence, the second objective of this paper is to show how the overall hardware can be reduced while still providing efficient beamforming. We thus propose a hybrid wavelength sensitive and wavelength insensitive processor design that can lead to the desired reduction in hardware.

Finally, the proposed beamforming hardware must meet military environment operational requirements, particularly, shock/vibrations and high temperature. Hence, all optical hardware used to achieve the first two objectives (i.e., VODL+VOA module plus hardware compressed processor) must be temperature and vibration robust. To meet this third and final program objective, we propose the use of a proven optical MEMS device technology that has already shown its strength on the environmental front.

Over the years, a host of technologies and methods have been used to propose and demonstrate VODLs [1]. The dominant method involves forming a binary switched delay line using a cascade of 1x2 or 2x2 optical switches. Key switch technologies used include liquid crystals [2], optomechanics, lithium niobate [3] and GaAs integrated-optics [4], bulk acousto-optics [5], and silica thermo-optics. Another key method involves delay via wavelength control such as via the use of fiber Bragg gratings [6] and dispersive fibers [7].

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The key thing to note is that all these methods and technologies require temperature control to varying degrees. In addition, none of these methods provide architecture or device level fault-tolerance. In addition, the switch crosstalk levels and speeds are not sufficient for fast tracking of targets. It was recognized in the early 1990s by GE [8] and TI [9] groups that MEMS-based optics could be used to form temperature robust VODLs for phased array applications. Work on VOAs has followed independently using similar technologies. Riza's early work did show how LC technology can be combined in the same processor to implement both VODL and VOA functions. Yet, so far, no flexible, temperature robust, fault-tolerant beamfomer module has been proposed that can be efficiently used for mult-beam radar controls.

In this paper, for the first time, we show how using robust digital MEMS technology, a high speed universal beamformer with intrinsic time delay and gain controls can be formed that gives both architecture and device level fault-tolerance. It is important to note that although optical MEMS switch approaches require milliseconds for operations, Nuonics macropixel or SMP approach produces 15 microseconds fast speeds using tiny micromirrors operated together.

2. TECHNICAL RATIONALE FOR THE PROPOSED PHOTONIC BEAMFORMER

Radar systems desire temperature robust optical systems that require little or no temperature controls. This saves cost, size, weight, and complexity of military systems. At present, MEMS chip scale device technology has shown the promise to be temperature insensitive. In particular, one optical MEMS technology called the TI DMD chip has demonstrated the MIL-STD883D test shown below [10]. Hence, we have chosen to construct our beamformer module using TI DMD optical MEMS technology.

Table showing MIL-STD883D test demonstrated in the TI DMD chip.

Test Type	Test description	MIL-STD 883D Reference
Thermal Shock	15 cycles, -25° to +100°C	Method 1011, Cond. B
Temperature Cycling	100 cycles, -25° to +100°C	Method 1010, Cond. A
Moisture Resistance	10 days, T-cycles, RH to +100%	Method 1004
Seal Integrity	Fine & gross leak	Method 1014, Cond. B1
Mechanical Shock	5 shock pulses, 6 axis, 1500 *g* peak, 0.5 ms pulse	Method 2002, Cond. B
Vibration	20 *g* peak, 20-2000 Hz, 3 axis, 40 ms pulse	Method 2007, Cond. A
Acceleration	10,000 *g*, Y axis, 1 minute	Method 2002, Cond. B

Second, radar systems require fault-tolerance to prevent catastrophic failure. The VODL and VOA are fundamental building blocks in the universal beamforming module that contains a single physical optical channel. For instance, if one switch or VOA fails, another switch in the module acting as spares can be used to complete operations. Also there is always a concern when using a moving parts device such as a MEMS device that a moving micromirror might stick, break, or fail proper operation. Hence, the MEMS device should also possess fault-tolerance. Hence, we have chosen to construct our module in such a way that both the module architecture via redundant switching units per chip and the optical MEMS device technology via the use of a macro-pixel per beam make the beamformer module fault-tolerant.

It is also important that a beamformer module be rapidly reconfigurable for tracking fast moving targets. Traditionally optical MEMS devices operate with slow millisecond rates. The TI DMD works at a fast 15 microsecond switching speed for digital operations as it is a small 13.8 micron x 13.8 micron mirror with small +/- 9.2 degree tilts. Collimated freespace beams from fibers have near millimeter diameter beams. Using our macro-pixel MEMS approach where one beam naturally interacts with many simultaneously driven micromirrors, a fast light beam processing is possible. Hence, our collective rationale for using the TI DMD and deploying one DMD/module approach. The details of these approaches is to follow in the next section. Note that a similar response can be obtained using a piston-type diffractive MEMS device.

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Example Delay line requirements.

Number of bits	6
RF Loss/bit	2 dB
Least Significant Bit (LSB)	0.1 ns
Most Significant Bit (LSB)	3.2 ns
Maximum Time Delay Error	0.05 ns
Frequency Range	DC-20 GHz
Within Channel Leakage Noise	< - 60 dB
RF Interchannel Crosstalk	< - 60 dB

Example VOA specs and switching time requirements for the VODL and VOA after command signal has been applied to the module connectors

Transmit to receive	15 μs
Time delay setting	15 μs
VOA Range	35 dB
VOA Resolution	0.1 dB
VOA Loss	< 1 dB

Tables above show parameters and associated numbers for a typical VODL and VOA for a phased array beamformer application. For instance, the VODL can have 6 bits, with a least significant bit (LSB) of 0.1 ns, and a most significant bit (MSB) of 3.2 ns. Numbers of < - 60 dB are desirable for both the within channel leakage noise and the RF interchannel crosstalk. The RF crosstalk between delay channels relates with the amount of the optical signal traveling through the desired path that leaks to the adjacent channels. The requirements for the VOA and VODL switching times after the command signal has been applied at the connector can be 15 microseconds. Typical VOA requirements indicate a 35 dB (or 70 dB RF) dynamic range, < 1 dB loss, and 0.1 dB optical resolution.

Estimated Requirements for an Ideal 1x2 FO switch for phased array controls.

1x2 FO Switch Parameter	**Switch Requirements**
Optical Insertion Loss	< 1dB
Switching Speed	15 microsecond
Optical Crosstalk (Extinction Ratio)	> 40 dB
Polarization Insensitive Operation	Yes; e.g., Very Low < 0.05 dB Polarization Dependent Loss (PDL) and very low (<0.01 ns) Polarization Mode Dispersion (PMD)
Temperature Insensitive Operation	Yes
Catastrophic Failure Elimination	Fault-tolerant design highly desirable
Simultaneous Optical Gain Control	Highly desirable for signal level calibration & array weighting functions for receive beamforming
Wavelength Sensitive Operation	Highly desirable over 1532-1610 nm WDM band; < 0.1 dB loss variations over band
Relative Path Delay between switch states	<0.01 ns (depends on phased array design)
Packaging & Cost	Amenable to large scale manufacturing & Space Qualification; Chip scale size and weight
Device Life Time	Better that 1 million switching cycles

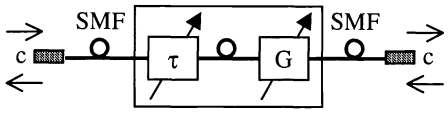
The proposed module technology can be adapted to be either wavelength sensitive and/or wavelength insensitive. This is done by the appropriate choice of the fiber, such as using fibers with multiple fiber Bragg gratings (FBGs) make the VODL wavelength sensitive. Thus advanced hardware compression techniques using multiple wavelengths can be used for radar controls, as done by us in prior work [11]

Because our VODL is based on a 1x2 fiber-optic (FO) switch, this switch must also meet very stringent requirements that are yet to be delivered. The Table earlier describes such estimated ideal requirements. Note that the environment plays a critical role for setting parameters for this switch; hence temperature robust MEMS technology is chosen for our switch design. Optical MEMS chips proposed for use in this paper have been developed over a decade of focused research and development by TI. A whole industry related to projection displays has been created by this TI chip,

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making it a high payoff low cost leverage for DOD technology use. The realization of a beamformer module based on this TI chip technology that is robust to temperature and is fault-tolerant is important attribute for future wideband radar systems that will most likely use both electronic digital beamforming and wideband photonic beamforming.

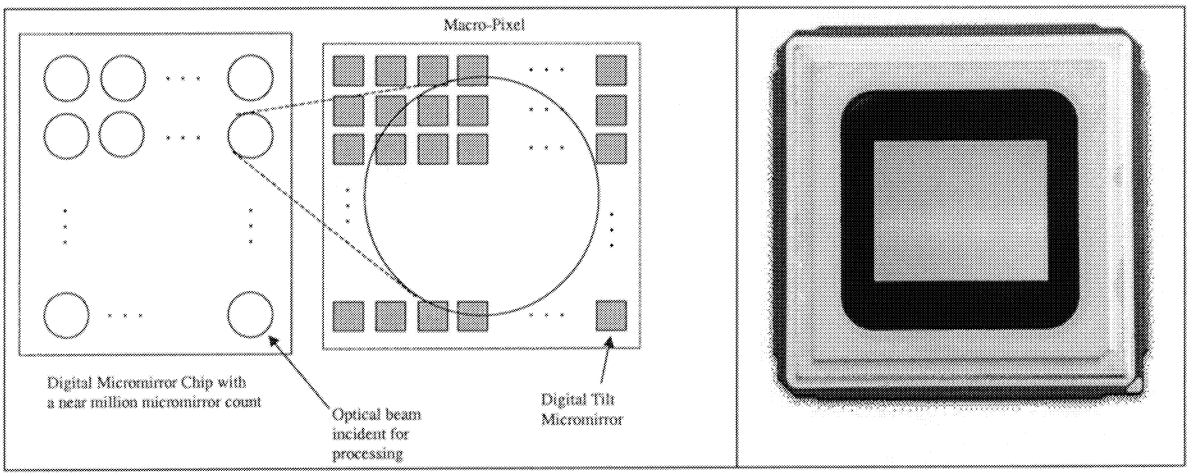
3. PROPOSED FAULT-TOLERANT MULTI-BEAM PHOTONIC BEAMFORMING



Universal Processor Module

Fig.1 The desired Universal Processor Module that can provide the VODL and VOA functions in one unit for one optical physical channel. "c" represents SMF connector or near zero loss fiber splice.

Fig.1 shows the proposed Universal Processor Module that can provide the VODL and VOA functions in one unit for one optical physical channel. In otherwords, the module has a fiber in port and a fiber out port, with ports being reversible if needed. Using this compact and flexible module, a full fledged multi-beam beamformer can be realized using an intelligent interconnection of module arrays.



(a) (b)

Fig.2 (a) The proposed Spatially Multiplexed Processing (SMP) MEMS approach to Photonic Beamformer Module Construction. (b) The infrared TI DMD chip used as the SMP optical MEMS chip.

One rectangular Texas Instruments (TI) Digital Micromirror Device (DMD) chip (Fig.2(b)) is used to form one flexible beamformer module. The chip has nearly 800,000 micromirrors, each squares of 15 micron x 15 microns. The collimated beam from each 1.8 mm diameter fiber collimator is around 1.6 mm in null-to-null diameters. Thus, each TI DMD chip can interface with many (e.g., 36) optical beams, as shown in Fig.2. Plus, each beam is controlled by a large number (e.g., 2000) micromirrors in a control site called macro-pixel. Note that each micromirror has digital operation that is 100 % repeatable versus analog mode controls. Because many parallel processing channels are present in one compact module, one digital VODL and digital VOA can be formed within a single module.

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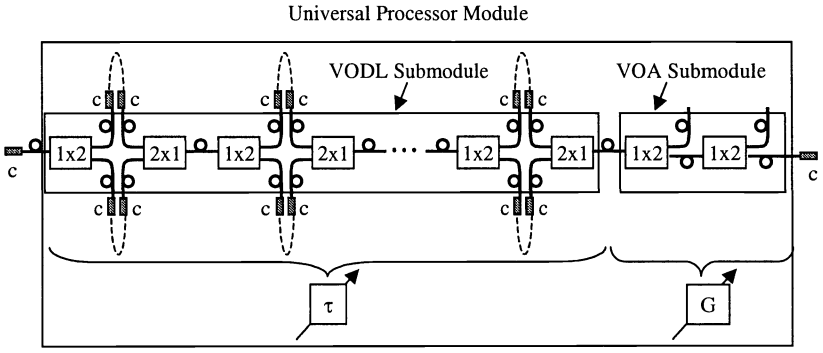


Fig.3. Inner workings of the proposed beamformer module.

Fig.3 shows what is contained within each beamformer module that contains a two stage signal processing sub-module where the first sub-module forms an N-bit VODL and the second submodule forms a digital VOA. The N-bit VODL consists of N VODL modules. Each VODL module is constructed by cascading a 1x2 fiber-optic (FO) switch with a 2x1 FO switch creating a relative delay architecture. Fig.4 shows a variety of fiber interconnections that can be used with the VODL. Two fibers (or their equivalent) of a given length are connected between the switches. The lower fiber is the reference fiber while the top fiber contributes to the regular mode time delay. The N-stages form a N-bit binary switched VODL. Based on relative fiber lengths, both short and long delays can be generated. Fig.4 also shows a wavelength sensitive delay using a low loss (< 0.6 dB) circulator and carefully placed fiber Bragg gratings (FBGs) to form a wavelength sensitive VODL bit. This approach will be used to reduce overall beamforming hardware. Note that since both output ports of the 1x2 switch are used for fiber delay controls, the fiber lengths between the two 1x2 interconnected switches can be designed to generate even very small delays.

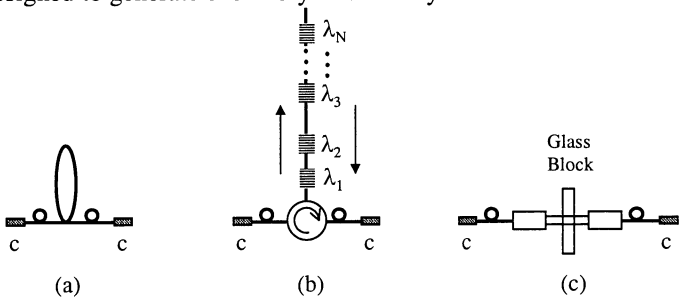


Fig.4. The variety of (a) SMF, (b) wavelength sensitive delay, and (c) solid-optic delay, options for fiber interconnections for the 1x2 switches in the proposed beamformer module.

The second stage in the beamformer module is the VOA sub-module. In Fig.3, the submodule by example has two 1x2 FO switches in cascade. Here, the switches are used as 1x1 switches with one output fiber inactive in each switch. Hence, light is attenuated by digitally controlling the number of micromirrors on the on (or relative tilt) state in a macropixel processing the beam input to this 1x2 switch. Two 1x2 switches can essentially double the dynamic range and resolution of the VOA control in the beamformer module. This attenuation capability is very helpful in radar beam shaping and RF transversal filtering applications where optical weighting of optical signals is required.

Light into the module is launched and collected after processing via single-mode fibers (SMFs) coupled to a gradient index (GRIN) FO collimators. 1-D arrays of collimators are used such as now available from LightPath Technologies. Each micromirror in the chip has two electronically settable tilt states. The first state is called a flat state where the micromirror directs the light to one fiber port. In the second state called the tilt state where the micromirror has tilted by say + 18.2° relative to the flat state, the input light is directed to the second fiber in a given 1x2 switch. Note that for VODL operations, all micromirrors in the chip are operated together in a given state; i.e., either all flat or all tilt state. In the case of gain control within the VOAs, some mirrors point to desired fiber port while others point to the optical reject power state.

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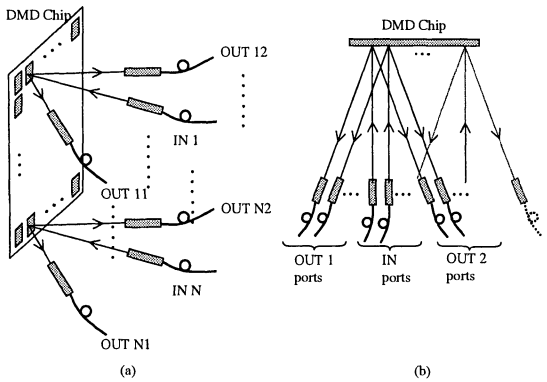


Figure 5: The proposed construction of the beamformer module using one DMD chip and linear arrays of fiber lens coupling optics. (a) 3-D view and (b) is top view. The distances between input and the two output ports per light processing site are designed to obey the low coupling loss self-imaging effect.

Fig.6. shows our proposed hardware compressed beamforming method using a cascade of wavelength sensitive and wavelength insensitive beamformer modules to reduce multi-beam photonic beamforming hardware. The figure shows the simple case of transmit mode single radar beam generation for a large array where sub-array partitioning is used. M wavelengths correspond to the M-element subarray in the J subarrays antenna system. The wavelength sensitive beamformer module produces the within subarray steering while the J independent wavelength insensitive beamformer modules called BMs produce bias delays to cause steering across the many sub-arrays. Hence, this approach uses J+1 proposed beamformer modules. Recall that the wavelength sensitive beamformer module is formed by using all FBG delays connected to the switching modules for the VODL sub-module in the beamformer module. To form multiple independent radar beams, multiple systems as shown in Fig.6 are required. It is clear that using multiple wavelengths greatly reduces the number of beamformer modules required for total multiple radar beam controls, hence our proposed approach. Although a single DMD device micromirror operates at a fast 15 microsec speed, faster radar beam controls are possible if we deploy time multiplexing of signal processing channels. In other words, when one radar beam is dwelling and using one active signal processing channel, the other signal processing channel can be reconfigured for setting the next radar beam. This way the speed of the electronic channel selection switch and the radar beam dwell time limits the radar scanning speed.

Fig.7 shows our potential antenna system configuration for a multi-beam radar demonstration in receive mode. The system has N antenna elements that feed N electrical-to optical (or E/O) converters that translate the N RF energy signals on to carefully chosen N optical carriers of N wavelengths. These N different wavelengths are combined using a N:1 optical wavelength division multiplexer (WDM) device and then launched into a single remoting optical fiber that travels to the beamformer site. On arrival, this multi-wavelength signal is split into Q parts using a 1:Q optical splitter device, where Q is the number of independent simultaneous radar beams required for the system. Each output from the splitter has multiple wavelengths that are then amplified by a multiwavelength optical amplifier (OA). The amplified optical signal is fed into a wavelength sensitive beamformer module, such as shown in Fig.8. Here the VODL is the same as in Fig.3 using FBGs shown in Fig.4(b) as delay elements. In this case, each FBG delay element will have N FBGs placed to give a given inter-antenna delay. Multiple such delay elements (one for each VODL bit) with different inter-antenna delay values are used to cover the desired radar beam scan range. Note that we use Q compact beamformer modules, where each module is a stand alone plug-in plug-out unit that provides both delay and per wavelength gain controls. Specifically, Fig.8 (unlike Fig.3) shows a VOA sub-module for multi-wavelength independent gain controls for radar calibration and beam shaping. Here, a WDM device is used to separate the wavelengths before being fed to the 1x2 (actually operated in 1x1 mode) control sites on the DMD to enable all-digital per wavelength attenuation controls. The N collected light signals are then fed to the optical-to-RF converters (photodetectors) before being sent to the N:1 RF combiner that generates the desired receive radar beam. To consider the feasibility of our technology for demonstration, the following design analysis is conducted. Assume N=10 elements and Q=10 beams. Hence the requirements are: (a) 10 lasers with 10 different wavelengths, (b) 10:1 WDM devices, (c) 11 WDM devices, (d) One 1:10 Optical Splitter/Coupler, (e) 100 photo-detectors, (f) 10:1 RF beam combiner, (g) 10 RF combiners, (h) 10 Wavelength sensitive beamformer modules. Given a 5-bit delay requirement, ten 1x2 switches are required for the 5-bit VODL and ten 1x2 (or 1x1) switches are needed for the 10-wavelength VOA array, each VOA with a 35 dB dynamic range. Hence, a total of 20 control sites on the DMD are required. Given the present IR TI DMD size, tilt angles, and collimator sizes, 5x7=35 control sites are expected per DMD (and hence proposed beamformer module). Ten DMDs will be required for a

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10-radar beam beamformer demonstration. Hence, it is practical to form the proposed antenna system using the proposed beamformer technology.

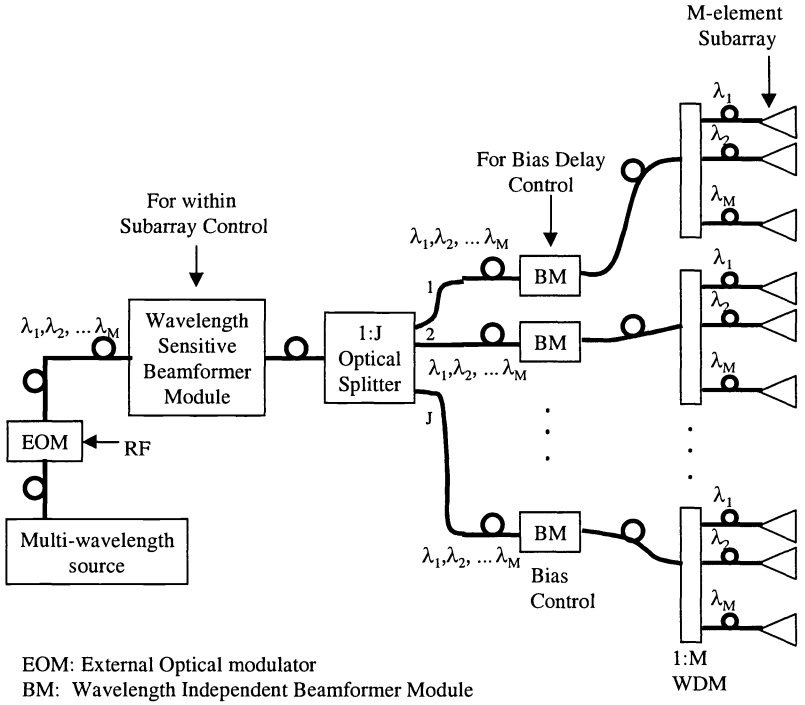


Fig.6. Our proposed hardware compressed beamforming method for the simpler to show transmit case using a cascade of wavelength sensitive and wavelength insensitive beamformer modules to reduce multi-beam photonic beamforming hardware.

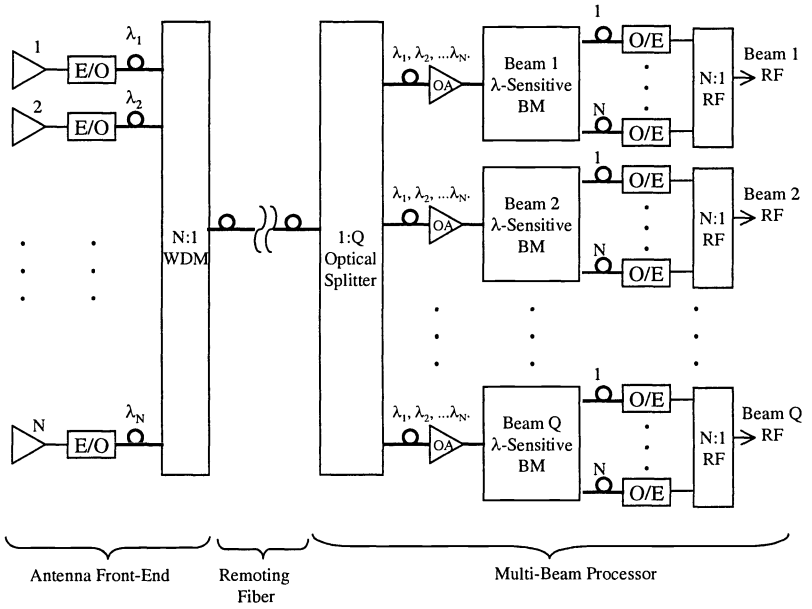


Fig.7. Proposed Receive-Mode Multi-Beam Array Antenna System using the proposed Nuonics compact beamformer modules.

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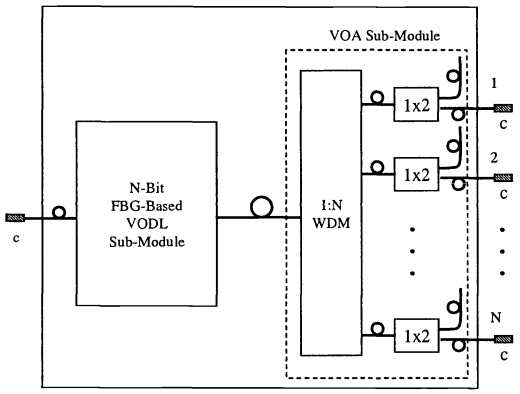


Fig.8. Proposed Wavelength Sensitive Beamformer Module that provides both optical signal time delay and gain controls on a wavelength sensitive basis.

4. FAULT-TOLERANT BY-PASS ARCHITECTURE

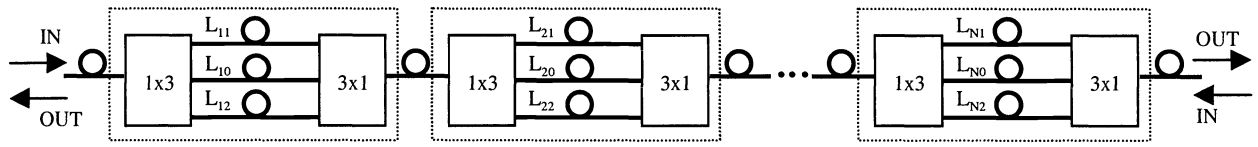


Fig.9 The proposed paradigm shifting fault-tolerant by-pass mode MEMS-based VODL where both the architecture and device level MEMS switch optics are fault-tolerant. Other benefits include faster speed and gain controls within the structure when compared to previous VODLs.

Next proposed in Fig.9 is optical hardware that is intrinsically fault tolerant; i.e., has two state redundancy for the VODL. As an example, if a fiber in a delay loop breaks, the redundant fiber is switched in for full VODL operations. The basic concept involves a bypass-mode switched VODL architecture consisting of N cascaded tri-state modules. Each module is a self-sufficient fully programmable delay line unit consisting of two fiber interconnected 1x3 switches. Each switch is a unique MEMS-based switch that is also fault-tolerant [21] via the use of a five (or more) micromirrors chip instead of a single large one micromirror chip. In addition, the use of smaller micromirrors allows a faster switch response. An added benefit of this switch is intrinsic gain control. The three delay fiber loops in each module can have any desired length based on application requirements. For module 1, the fiber lengths are L_{10}, L_{11}, and L_{12} where L_{10} can be the reference delay fiber. Hence, L_{11} and L_{12} can take values either greater than or smaller than L_{10} to generate positive or negative delays. To operate the module in the fault-tolerant mode, $L_{11} = L_{12}$. In this way, if the L_{11} fiber breaks or the related switch port malfunctions, the L_{12} fiber comes into action, thus preventing VODL catastrophic failure and providing same time delay values. The proposed VODL has the unique capability to double the time delay range of a N-stage binary delay line, thus providing a compact mechanism to form signal processing units. The proposed VODL is also optically reversible in nature.

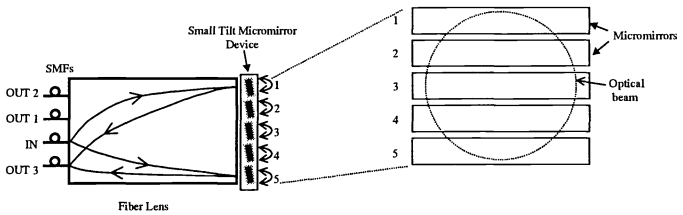


Fig.10. The proposed fault-tolerant 1x3 FO switch. The MEMS chip has for example five micromirrors to provide fault-tolerance to an otherwise single point catastrophic failure device.

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Fig.10 shows the proposed fault-tolerant 1x3 FO switch design based on a single fiber lens and a small tilt MEMS mirror chip (a piston type diffractive MEMS chip can also be used). Specifically, this example MEMS mirror chip has five independent micromirrors that gives a factor of five fault-tolerance for a moving parts device. The micromirrors tilt to generate a tri-state device, i.e., flat (IN to OUT1), tilt1 (IN to OUT2), and tilt2 (IN to OUT3), to couple to the correct fiber. The micromirror sizes have to be correctly designed to give equal light weighting for all mirrors. This way, if one mirror fails, you only lose 1/5 the light in the total beam. Referring back to Fig.9, the N-stage VODL consists of N VODL modules. Each VODL module is constructed by cascading a 1x3 FO switch with a 3x1 FO switch creating a by-pass architecture. Three fibers of a given length are connected between the switches. The central fiber is the reference fiber while the top fiber contributes to the regular mode time delay. The lower fiber kicks in when the VODL module operates in its fail-safe mode. Both top and bottom fibers are of equal length for fault-tolerant VODL operations. The N-stages form a N-bit binary switched VODL. Based on relative fiber lengths, both short and long delays can be generated. The fail safe ports of the FO switches can be used to direct light out of the main signal path causing optical attenuation controls. Because each FO switch has light guided by a five micromirror chip, the desired number of mirrors can be pointed to the fail safe fiber-port to cause attenuation. Also, since there are two such switches per ODL module, a doubling attenuation effect occurs. Furthermore there are N stages, hence N times a single module attenuation can be generated. This implies that the proposed VODL technology has intrinsic attenuation controls. This capability is very helpful in radar beam shaping and RF transversal filtering applications where optical weighting of optical signals is required.The proposed by-pass VODL has another unique capability that via the proper choice of the fiber lengths, generates a doubling of the time delay dynamic range. The approach is to design each module with positive and negative time delays with regards to the central reference fiber. For instance at the Nth module, $L_{N1} = L_{N0} - c\,\tau\,2^{N-1}$ and $L_{N2} = L_{N0} + c\,\tau\,2^{N-1}$, where c is the speed of light in the fiber. When designing such a VODL, the total reference delay $N\,L > (2^N - 1)\,c\,\tau$, where L is the central reference delay used for all the modules. Hence, this VODL gives a time delay range of 2 $(2^N - 1)\,c\,\tau$, with a τ resolution, hence doubling the time delay range from either the upper or lower N-bit VODL. The L_{n1} fibers correspond to the upper VODL while the L_{n2} fibers correspond to the lower VODL in Fig.9. In effect, the proposed by-pass architecture VODL is a combination of two binary switched VODLs, where one VODL adds delay and another reduces delay. Hence, this example shows the versatility of the proposed fault-tolerant VODL architecture.

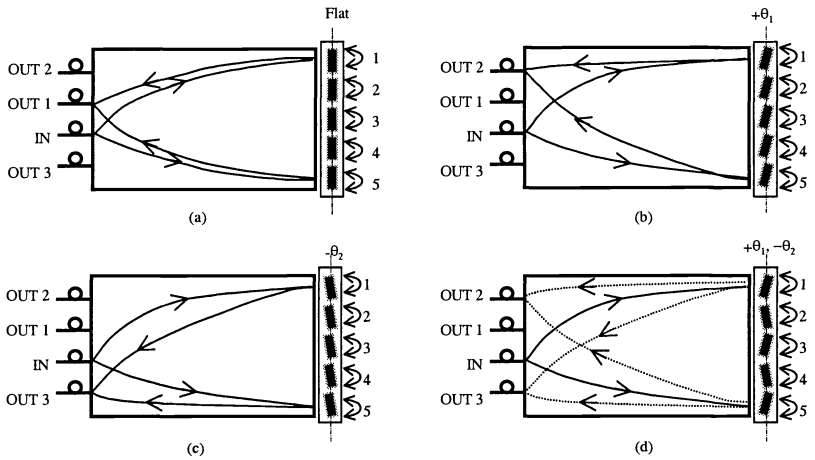


Figure11: The 1x3 fault-tolerant MEMS optical switch used to realize the proposed VODL. Switch states are (a) Straight state (zero relative delay), (b) Exchanging state 1 (delay mode), (c) Exchanging state 2 (fail-safe mode), and (d) Intrinsic gain control mode.

The proposed VODL uses special 1x3 FO switches shown in Fig.11. Light is launched into the switch via the near centrally located single-mode fiber (SMF) in the four SMF arrangement that is coupled to a gradient index (GRIN) fiber-optic (FO) collimator. The collimator is coupled on the other side to an optical MEMS chip that is based on small tilt (e.g., $< \pm 4°$ tilt) micromirrors. The small tilt is important for generating the small motion that can lead to fast switching times for the micromirror positioning. The unique MEMS chip is based on using a macro-pixel to control the beam path. All mechanical objects have inertia which leads to a design trade-off between speed of operation and size of mechanical element. Hence, in order to make a mirror switch faster, the mirror physical size should be made smaller and also the mirror should implement switching operation via a small motion of mechanical element. The problem lies in the fact that

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a smaller mirror is harder to align with the smaller (or even totally focussed) optical beam, leading to a mechanically sensitive package. It would be nice to pick up switching speed while still maintaining a large target to hit with the optical beam. It would also be nice to add robustness to single point mechanical failure in the case that the single large mirror fails. All these problems are solved using the macro-pixel concept where the single large mirror is replaced by a few smaller size mirrors, each with independent controls. Furthermore, each mirror implements full switching via operating in a small tilt mode that lends itself to faster switching times. Fig.11 shows an example where 5 such micromirrors are used to control the incident collimated beam that typically has a 0.6 $1/e^2$ diameter Gaussian profile. Hence, here you have a 1/5 failure rate compared to a single mirror mechanically implemented optical component. This feature is particularly attractive for low maintenance radar applications where fault-tolerance should be built into all hardware. The operation of the switch is as follows. Each micromirror in the chip has three electronically settable tilt states. The first state with zero voltage drive is called a flat state where the micromirror is flat. The second state with a given voltage level drive is called the tilt state where the micromirror has tilted by say θ_1 degrees (e.g., + 4°) relative to the flat state. The third state with a given voltage level drive is called the tilt state where the micromirror has tilted by say $\theta 2$ degrees (e.g., - 4°.) relative to the flat state. Note that all micromirrors in the chip are operated together in a given state; i.e., either all flat or all tilt state for regular mode or fail safe mode. In case gain control is required, some mirrors point to desired fiber port while others point to the optical reject power state (see Fig.11.d). In the MEMS device flat state, light enters through the IN fiber port and goes out through the OUT1 fiber port (the reverse path also works). This is called the straight no-delay state of the switch. In the MEMS device tilt state, light from IN goes to OUT2 (the reverse path also works). This is called the exchanging or delay state. In the MEMS device fail safe mode tilt state, light from IN goes to OUT3 (the reverse path also works). This is called the fail safe exchanging state. As mentioned, for each switch state, all micromirrors in the chip are operated in unison and in the same state unless intrinsic optical attenuation controls is also required.

The fault-tolerant by-pass architecture features: (a) Intrinsic Device Fault-tolerance: Because the proposed optical chip uses multiple optical control elements (e.g., five near same size micromirrors) to implement tri-state switching, single point optical switch catastrophic failure is avoided. This fault-tolerance is critical in radar scenarios where total device failure should be eliminated. Partial failure also gives early warning of VODL malfunction that can lead to timely system repair and maintenance. (b) Intrinsic Optical Attenuation Controls: This VODL can provide intrinsic gain controls as the fault-tolerant multi-mirror chip design with the Bypass VODL architecture allows the proper routing of unwanted light that leads to attenuation. Furthermore, the cascading effect of modules within the VODL leads to a powerful N-stage controlled fiber-optic attenuator. (c) Upgradeable Design: The VODL performance can be easily upgraded by re-programming the by-pass optics. For instance, the optical chip in the tri-state switch can be wired through software to upgrade to more advanced system requirements as for instance time delay beamforming needs change to wider time delay ranges. The proposed architecture is also modular so VODLs can be easily upgraded by attaching in serial additional VODL modules. (d) Low Cost Batch Fabrication via MEMS: The proposed chip used in the tri-state switch is a Microelectromechanical Systems (MEMS) micromirror chip (can be tilt or piston-type micromirrors) that is amenable to large scale volume manufacturing that also allows production of several chips on the same substrate. This leads to low cost mirror arrays such as needed in most radar applications. MEMS is particularly attractive for the harsh radar environment with severe temperature conditions.

5. CONCLUSION

Previous efforts to make photonic beamformers have not produced modular fault-tolerant temperature robust modules. This is the first time to this best of our knowledge that we propose such a module. There are several important parameters of our proposed beamformer module, and preliminary analysis for these parameters indicates the following promising results.

- Switched Delay isolation/crosstalk: The optical isolation between the two switching states is expected to be high (>40 dB) as the TI DMD is designed as a blazed grating and coupling off-axis light (e.g., diffraction orders) back into SMFs is very difficult.
- Backreflection levels: The backreflection levels are dependent on the optical power that is reflected back from the optical elements into the input ports. Because our switch in the beamformer has an off-optical axis configuration, back-reflections are not routed back to the inputs. Thus, the main source of optical backreflection is the optical-fiber GRIN-lens interface of the FO collimator. GRIN-lens FO-collimators with backreflection levels of <-60 dB are commercially available, e.g., by OZ Optics [12].
- Optical insertion loss: The optical insertion loss per strike on the DMD depends on four parameters. These are the losses from the DMD due to the optical quality of micromirrors, the fill factor of the macro-pixel, the coupling

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efficiency between SMF ports, and the reflection losses from all the optical components. Based on our recent correspondence with TI, the TI DMD has a 0.6 dB loss per reflection due to the mirror coating, IR window, and fill factor plus diffraction effect. Using our earlier proposed self-imaging mechanism for low loss coupling between fiber lenses, an additional 0.3 dB loss is expected per fiber-to-fiber coupling in beamformer module. Hence, a total loss of < 1 dB is expected per fiber-to-fiber interconnection in module, making switch cascading practical.

- Polarization Independence: Fundamentally, the broadband reflective mirror coating on the TI DMD provides polarization independence.
- Wavelength Independence: The wavelength dependence of our module depends on the wavelength dependence of the fiber collimator and the macro-pixel MEMS DMD chip design & its coating. The measured optical loss fluctuation over a 70-nm optical bandwidth centered @ 1550nm for the fiber collimator-mirror pair used in our earlier demonstration was $\pm$ 0.04 dB [13]. Thus, with the insertion of the MEMS chip having a very coarse grating-like pattern in the structure, the expected wavelength dependent loss for our proposed switch is < $\pm$ 0.1 dB. Thus, our module is wavelength independent although the VODL can be λ sensitive.
- Switching Speed: The switching speed is 15 microseconds based on TI DMD micromirror response. This can be considered perhaps as the only disadvantage of our approach if faster random access beam scan times are required. If such is the radar application, we propose to use a time multiplexing beam scanning method as also shown by us earlier. This method can enable a faster (e.g., sub-microseconds) radar scanning speed if radar beam scan orders are known *apriori* [14,15].
- Fault-Tolerance: As described earlier, if a few micromirrors in a macro-pixel are malfunctioning, our switching and attenuation control sites on the DMD can still be operated using the remaining functional micromirrors, thus leading to a fault-tolerant module design, with a tradeoff between loss and fault-tolerance.
- Relative Path-length Delays and Optical Light Flow Reversibility: The proposed module is fully reversible. The input and output ports are interchangeable, and thus light can propagate through the system in both directions with essentially zero relative path delay due to the near symmetry of the out port locations with respect to the input port.
- Temperature Independence: With the use of a hermetic seal such as demonstrated in the MILSPEC TI DMD chip, our module is expected to pass the MIL-STD 883D test.
- Compact Size: Since all optical components used in our module are categorized as micro-optics, a compact 10 cm x 10 cm x 10 cm beamformer module can be achieved.
- Low Cost Packaging: Due to the use of low cost off-the-shelf fiber-optic GRIN lens 1-D arrays (such as the new Vectra Series from LightPath Tech.) and a mass produced TI MEMS DMD chip coupled in a simple compact near in-line architecture, low cost packaging is attainable over large production volumes.
- Power Consumption: Because of the capacitive electrostatic drive mechanism of the proposed DMD MEMS chip, almost negligible continuous wave electric power is required for module operation.
- Time Delay Scalability: The symmetric optical architecture allows time delays from picoseconds to tens of nanoseconds and beyond.
- Time Delay Wavelength Flexibility: The module provides an interconnection platform to connect both wavelength insensitive and wavelength sensitive (e.g., using FBGs) optical delays.
- Intrinsic Optical Attenuation Controls: Each VOA via the DMD can produce a 35 dB attenuation dynamic range with near 10 bit control. Two VOAs in cascade as proposed earlier can give a 70 dB optical or 140 dB RF gain control via our proposed approach.

The proposed beamformer requires the knowledge of various technology areas that includes (a) radar beamforming techniques and systems, (b) MEMS technology applications, (c) Optical phase, amplitude, and time delay control modules using optics, and (d) experience in the design of fiber-optically fed freespace parallel processors. In each of these core areas, we have made early contributions that include:

-- use of TI DMD for optical attenuation [16] and time delay controls [17],
-- use of fiber-optics to interface to freespace optical systems [18,19],
-- use of bulk-optics to form multichannel freespace/solid optics delay lines [20] .

Hence, the mentioned advantages of our beamformer module versus other optical methods make it a unique and highly desirable wideband radar technology to complement other existing radar technologies such as digital beamforming.

Also proposed is a fault-tolerant MEMS VODL technology that is particularly suited for implementing the time delay function in a wide variety of microwave photonic systems. The technology also has the potential for implementing other useful fiber-optic modules such as used in optical communications and coding.

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