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Universal Optical Code Division Multiple Access (O-CDMA) Encoders/Decoders

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1. INTRODUCTION

The ideal fiber-optic O-CDMA encoder/decoder technology should be able to simultaneously (a) select the desired optical bandwidth, i.e., the wavelength range of the coded signaling channel, e.g., 1500 nm to 1600 nm, to optimize efficient use of spectrum and power to match network load needs, (b) select the spectral location and number of processed channels in the wavelength spectrum, e.g., 100 channels, each with a 1 nm spectrum and a 1 nm equidistant channel spacing, to optimize crosstalk reduction, (c) select the optical power in each wavelength channel for calibration, equalization, and/or spectral shaping to account for spectral characteristics of other optical networking components, (d) select the number of replicas to be produced for each wavelength channel, i.e., the number of time delayed versions of a given wavelength channel in order to improve code weight and hence network Bit Error Rate (BER), (e) select the optical power in each of the time delayed replicas of the wavelength channel so as to preserve code orthogonality and reduce erroneous bit detection and (f) select the value of the time delays for each of the replicas of the wavelength channel across all wavelength channels in order to match code weight and data bit rate requirements. Time delays can range from several nanoseconds to sub-picoseconds and less. In addition, this ideal fiber-optic encoder/decoder technology should have the capability to be used with (a) Both incoherent processing-based O-CDMA and coherent ultrafast short-pulse based O-CDMA techniques for data transmission and (b) Free-space communications O-CDMA techniques such as Spatial CDMA and (c) be Modular in design to easily upgrade code/user numbers and code weights.

The ideal encoder/decoder therefore allows the intelligent realization of the optimum code for the given O-CDMA scenario and data multi-media content. In otherwords, ideal realization of code weight (e.g., number of 1's in a two dimensional (2-D) binary wavelength-time (λ-t) code matrix) and size (number of wavelength channels and number of time delay bits; 1 bit = data bit duration) are achievable so as to realize the full potential of O-CDMA communications in terms of Bit Error Rate (BER, e.g., > 10E-9), total users (number of codes, e.g., > 1000), and number of simultaneous users (e.g., > 100). Today, no such ideal encoder/decoder technology exists.

In this paper, we propose a unique solution that can for the first time realize this universal O-CDMA encoder/decoder. Our approach simultaneously meets all the previously listed challenges required for enabling this ideal O-CDMA hardware, thus promising a high pay-off to the area of secure optical communications. We propose a paradigm shift from how one has previously built fiber-optic O-CDMA encoders/decoders. Specifically, a " Hybrid Spatially Multiplexed Processing (SMP)" paradigm has been proposed that for the first time simultaneously brings all the required features to realize a truly intelligent, flexible, and modular O-CDMA encoder/decoder technology. In particular, the positive attributes of digital optical microelectromechanical systems (MEMS) are for the first time combined with the capabilities of analog liquid crystal (LC) optics to realize modular encoder/decoder designs that enable the proposed universal O-CDMA coding/decoding hardware.

Dual-material technologies are pursued as LC encoders/decoders can provide ultra-high resolution coding controls (e.g., ultrashort time delays with superfine wavelength control) within a no-moving parts environment while MEMS-based encoders/decoders can provide a polarization independent and temperature robust platform for wide dynamic range (e.g., large time delays in several nanoseconds for long code lengths) coding controls. In effect, the hybrid LC-MEMS approach combines the powerful capabilities of both technologies resulting in a universal O-CDMA encoder/decoder technology.

Over the years, it has become clear that O-CDMA communications (both using ultrashort coherent pulses [1,2] and incoherent processing methods [3-7] can improve its power by increasing the dimensionality of data coding [8,9]. In coherent O-CDMA, the difficulty lies in correctly tracking the carrier phase to properly recover the data [10]. This inturn leads to higher complexity in the receiver. Because coherent O-CDMA uses bi-polar coding of phase information, high

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processing gains can be achieved. On the otherhand, incoherent OCDMA uses unipolar codes but simple direct detection receivers, although at lower processing gains. Thus, the objective would be to develop an O-CDMA method that uses simple receivers but still has high processing gains for excellents BERs. The approach we have taken gives the capability to generate very high dimensionality O-CDMA codes, greatly benefiting the simpler and more practical incoherent OCDMA. In addition, our encoder/decoder technology can also help coherent O-CDMA via the use of the high resolution proposed LC-based O-CDMA encoder/decoder. Fundamentally, these are the advantages of our proposed technology to realize the ideal encoder\decoder technology. Other positive attributes of our technology, particularly, the MEMS designs includes broadband operations, low electrical power consumption, fast reconfiguration times, polarization independence, and temperature robustness.

Unsuccessful attempts to realize ideal multidimensional O-CDMA encoders/decoders have been made with various limited flexibility, fixed and minimal time dynamic range, and limited coding bandwidth product technologies. These include discrete technologies such as using pixelated LC devices for ultrashort pulse spectral coding [11], fixed and tunable fiber Bragg gratings [12-17], arrayed waveguide (AWG) multiplexer devices [18]. So far, to our knowledge, no such ideal technology exists.

On the disadvantage point of view, our technology requires innovations in optical design to implement compact robust packaging of freespace and bulk-optics. Fortunately, many similarities exists with the telecommunications industry that has matured bulk-optic packaging techniques such as for key components we use such as gratings, circulars, QWP, DMDs, LC SLMs, and mirrors.

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

-- spatial O-CDMA concepts for both freespace [19,20] and multi-fiber [21]and single-fiber communications [22],
-- use of TI DMD for optical attenuation [23]and time delay controls [24],
-- use of LC devices for optical phase controls [25],
-- use of fiber-optics to interface to freespace optical systems [26],
-- use of bulk gratings to form wavelength dispersive scanners [27] and
-- use of bulk-optics to form multichannel freespace/solid optics delay lines [28].

2. PROPOSED UNIVERSAL OCDMA ENCODER/DECODER DESIGN

To begin with, we start with the coherent or incoherent broadband optical signal s(t) that contains many optical wavelengths in a continuous spectrum or possibly discrete prearranged wavelengths. Fig.1(a) assumes the case of a continuous optical spectrum that is optically mapped on to a two dimensional spatial form where wavelengths are spatially dispersed along the x or λ direction and optical power within each wavelength is spatially distributed along the orthogonal y-direction. Next, in Fig.1(b), the selection of individual wavelengths or wavelength bands and their respective interchannel spacings is selected by x-direction pixel selection of 2-D optical spatial light modulator (SLM) devices within the encoder/decoder hardware. Following this important spectral slicing and allocation process, the maximum number of time delayed replicas for each wavelength channel is selected by y-direction pixel selection of the 2-D optical SLM devices within the encoder/decoder hardware. As shown in Fig.1(b), N discrete wavelengths are selected with equal inter-wavelength gaps. In addition, each wavelength channel is divided into M equal power spatial regions (see Fig.1(c)), creating an N x M wavelength-power 2-D spatial map. Since there are M possible replicas for a given wavelength, there can be a maximum of M delay steps (see Fig.1(d)) for any given wavelength, where a delay step is inverse of the data bit rate, and is given by τ. In otherwords, signals at a given wavelength can be generated with delays given as τ, 2τ, 3τ, 4τ,....$M\tau$. The allocation of delays within the wavelength-power map is drawn in the third dimension indicated via the time t index, and is M boxes deep. For universal multi-dimensional O-CDMA code selection, for each code, a different number of time delayed replicas out of a maximum M are chosen per wavelength across all N wavelengths, where the sum of total number of replicas for all wavelengths is the code weight "w". It is well known that a higher code weight can deliver much improved O-CDMA network features in terms of orthogonality of codes/users, inter-user crosstalk, BER, number of users/codes, and receiver discrimination sensitivity.

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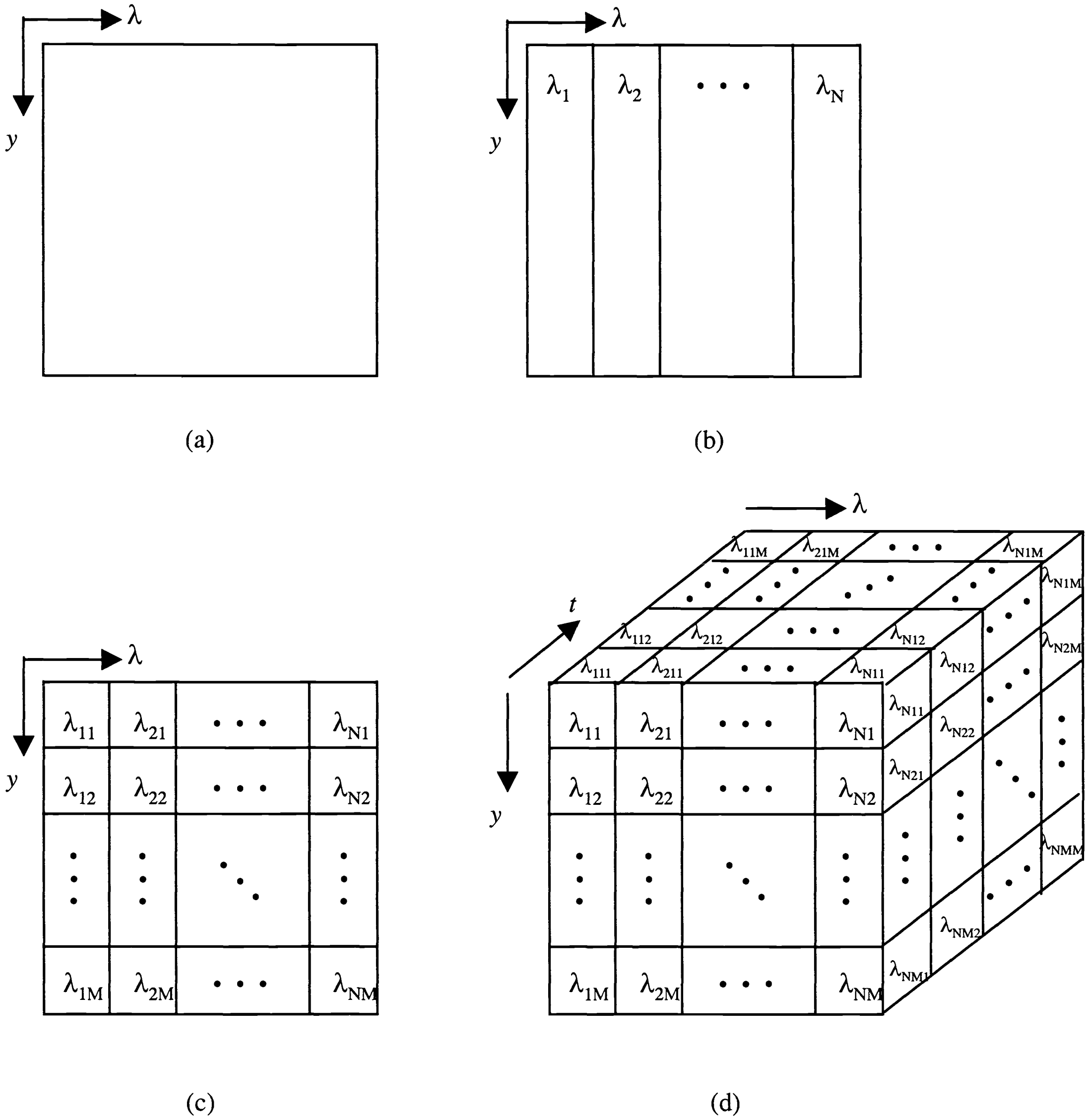

Fig.1 shows the logic behind the mathematical and physical properties required to realize the ultimate multi-dimensional codes required for scalable and secure O-CDMA fiber networks.

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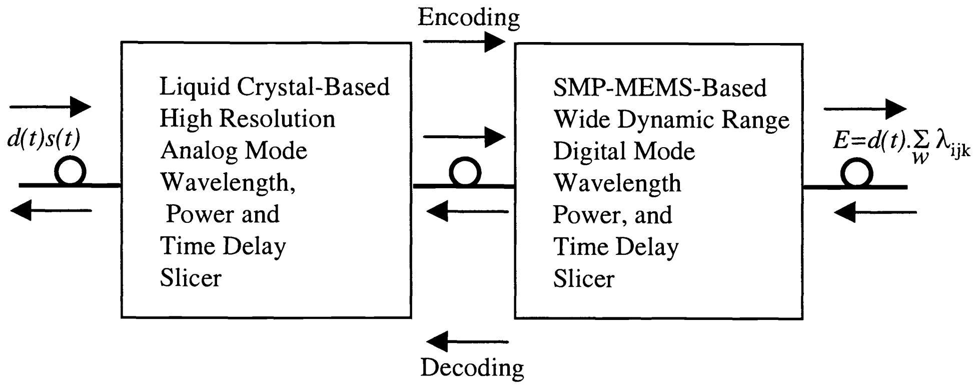

Fig.2 shows a block diagram of the proposed technical approach to realize the highly desired O-CDMA encoder/decoder that meets the stringent requirements for the ideal O-CDMA coding/decoding hardware.

Fig.2 shows the basic technology block diagram as to how the mathematical and physical steps in Fig.1 for ultimate O-CDMA code generation are implemented via a unique hybrid LC-MEMS SMP O-CDMA encoder/decoder technology. Fundamental to the proposed approach is the use of a pixel-free no-moving parts pure analog-mode LC device technology to form a high resolution wavelength, power, and time delay slicer to encode/decode an O-CDMA data signal d(t). The fact that the LC devices used incorporate a pixel-free format means that ultra-high spatial resolution is possible for spatial slicing of the wavelength-power 2-D space map. In addition, because the LC devices are operated in a pure smooth analog optical delay mode, very fine optical time delays can be imposed on signal replicas that generate the O-CDMA code. It is important to point out that these new LC device features are possible via very recent advancements in LC device technology such as via Hamamatu Corp.'s optically addressed birefringent-mode (BM) nematic liquid crystal (NLC) SLM.

The second fundamental block in the proposed encoder/decoder design is a SMP MEMS-based wide dynamic range all-digital mode wavelength, power, and time delay slicer. Here, switched all-digital robust processing is used to select the signals from the wavelength-power-time delay map to generate the O-CDMA codes. As the process is digital, discrete wavelengths and delays are generated. The delays come via an N-bit multichannel photonic delay line (PDL) implemented with the use of 2-D DMDs. Very recently, TI has modified its visible band projection display DMD for applications in the 1500-1600 nm band, such as in commercial optical telecommunications. This device has over 1 million individual mirrors, forming a 1000 x 1000 grid. Similarly, LC SLMs for writing on the Hamamatu SLM have one million pixel space-bandwidth products.

Fundamental to our proposed SMP approach is the intelligent use of this very large 1000 x 1000 SLM pixel grid to produce the desired wavelength-power 2-D maps for O-CDMA encoding/decoding. In essence, a 1000 wavelength slicing can take place with each wavelength sliced in power 1000 times. Furthermore, if a 10-bit delay can be generated via the combined LC (Analog) + MEMS (digital) variable delay lines, a total O-CDMA code multi-dimensional information capacity of over 1 billion (i.e., 1000 wavelengths, 1024 time delays, 1000 equally powered replicas/wavelength) can be realized, leading to unprecedented flexibility in code selection, simultaneous user upgrades, total user upgrades, and generally, the universal nature of the deployed O-CDMA network reconfigurability. These mentioned capabilities will be possible via our unique SMP LC-MEMS O-CDMA encoder/decoder technology.

3. PROPOSED UNIVERSAL OCDMA ENCODER/DECODER HARDWARE IMPLEMENTATIONS

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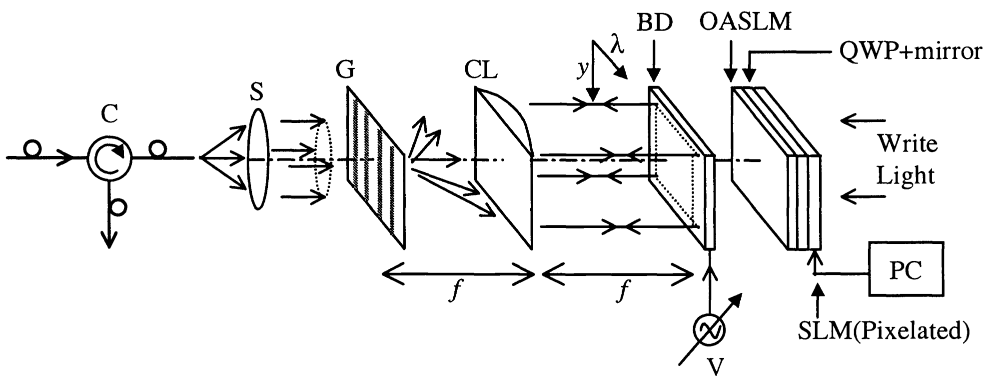

Fig.3 The proposed approach to realize the analog LC-based high resolution O-CDMA encoder/decoder.

Fig.3 shows our proposed LC-based high resolution O-CDMA encoder/decoder. Data modulated temporally broadband light from a coherent (e.g., femtosecond laser) or incoherent (amongst the wavelengths) source (e.g., Amplified spontaneous emission (ASE) of an Erbium-doped fiber amplifier (EDFA)) enters the module via a fiber-optic circulator C. Note that today, a typical circulator is a compact and robust passive optical device with under 0.6 dB fiber-to-fiber optical loss (e.g., the Oplink Corp. device), thus making a practical option for insertion into an encoder/decoder. Light exiting the bare single mode fiber (SMF) expands into a compact (< 1.5 cm diameter collimator spherical lens S that generates a collimated Gaussian beam. This beam strikes a high efficiency broadband diffraction grating G that disperses the beam optical spectrum along the labelled λ direction. A cylindrical lens CL is used to make the spectral dispersed beams collinear as they generate the wavelength-power 2-D spatial map in the λ –y coordinates. Note that the cylindrical lens operates as a spatial Fourier transformer. As we are using Gaussian beam optics, the input spatial Gaussian beam stay Gaussian at the Fourier output plane, creating vertical strips of optical power across all wavelength in the input beam spectrum. We call the combination of S, G, and CL devices an optical wavelength-space mapper. Note that for simplicity, a transmissive grating is shown. In a practical scenario, a blazed reflection-type diffraction grating operated in the high efficiency (> 90 %) Littrow configuration is used in the optical design. The focal length F of the cylinder determines the size of the 2-D spatial map that interfaces to the LC-optics that implements coding. A typical size for F=10 cm and the spatial map is 1 cm x 1 cm. The 2-D map first passes via a thick (e.g., d=50 micron LC layer) parallel-rub NLC cell with one large (e.g, 1.5 cm x 1.5 cm) pixel driven by a 1-5 V 1KHz square wave. The nematic director of the NLC cell labelled BD for bias delay points in the y-direction. Hence, light with a polarization along y-direction acquires a time delay of d= n(v)d/c while of the orthogonal x-direction acquires a time delay of d= n d/c. Here c is the speed of light in air, n(v) is the voltage controlled index of reflection of the LC, and n is the fixed ordinary index of refraction of the LC.

Next, the light passes via a similar NLC director orientation NLC device labelled as the optically addressed SLM or OASLM. Again, the vertically and horizontally polarized light beams undergo a similar time delay allocation with the vertical beams picking up a programmed delay and the horizontal polarizations getting a fixed delay. The key difference this time is that the spatial allocation and value of imparted delays is controlled by the shape and power of the write light intensity falling on the back-face of the OASLM. Thus, by programming an analog image on say a 1000x1000 pixel transmissive NLC SLM such as available from Hamamatsu, any allocation of fine time delays (as d is usually 6-10 microns) is imparted on the different wavelength columns in the 2-D wavelength-power spatial map. In particular, the number of power divisions to generate different time delay signals at the same wavelength is controlled by the vertical slicing of the image written on the OASLM. Similarly, the horizontal direction wavelength slicing on the beam is controlled by the pitch of the vertical columns on the write image. Thus, the OASLM provides total high resolution flexibility as to how to slice the wavelength and power (or number of replicas with different time delays) for the input modulated broadband optical signal required for O-CDMA.

Furthermore, the analog control of both the BD and OASLM allows fine and accurate control of time delays within fine zones across a large time delay zone set by the range of the BD device. This allows for enhanced calibration capabilites for the overall encoder/decoder. Note that after processing through BD and OASLM, the light polarizations are flipped and this time the original input horizontal polarization (is flipped to vertical) via quarter-wave plate (QWP) and mirror

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acquires the desired programmed delays. Hence, both polarizations acquire the same delays, making a polarization independent encoder/decoder design, a must when using SMFs for communications. From a broadband operation point-of-view, NLCs work over large (e.g., 1300-1600 nm) near infrared bands. Any slight variations in index can be calibrated into the device via write light power control as each wavelength is spatially separated for processing. The module is Fig.3 is ideal for ultrashort pulse coherent O-CDMA. In addition, it can also be used for high resolution processing during incoherent O-CDMA encoding/decoding when combined with the proposed high dynamic range MEMS-based encoder/decoder module shown now in Fig.4.

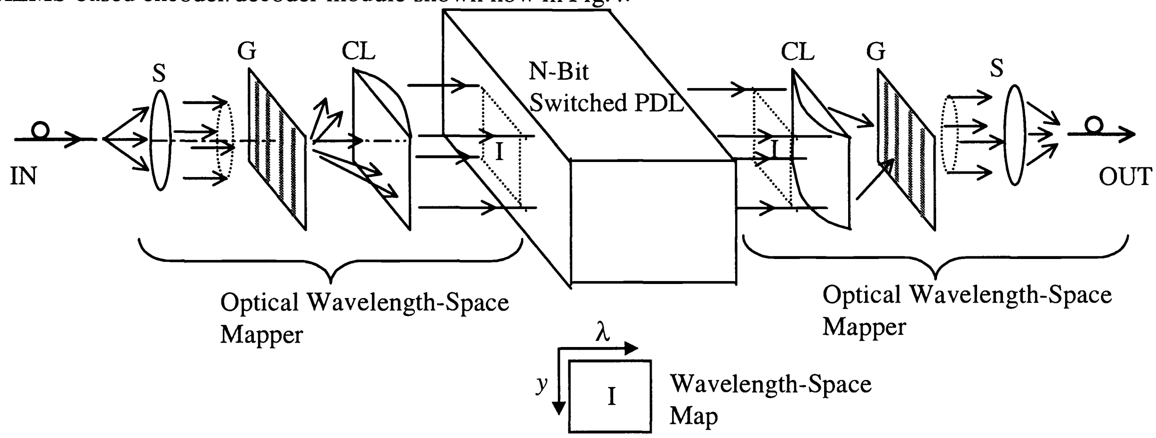

Fig.4 The proposed approach to realize the digital MEMS-based high dynamic range O-CDMA encoder/decoder.

Fig.4 shows the high dynamic range O-CDMA encoder/decoder structure where an N-bit switched multichannel photonic delay line (PDL) is sandwiched between two optical wavelength-space mappers (as in Fig.3). Hence, the input and output PDL ports see the input and processed wavelength-space 2-D optical maps "I", represented as frozen images. Slicing in terms of wavelengths, optical power/wavelength, and time delay values imparted per wavelength replica takes place within the MEMS-based PDL.

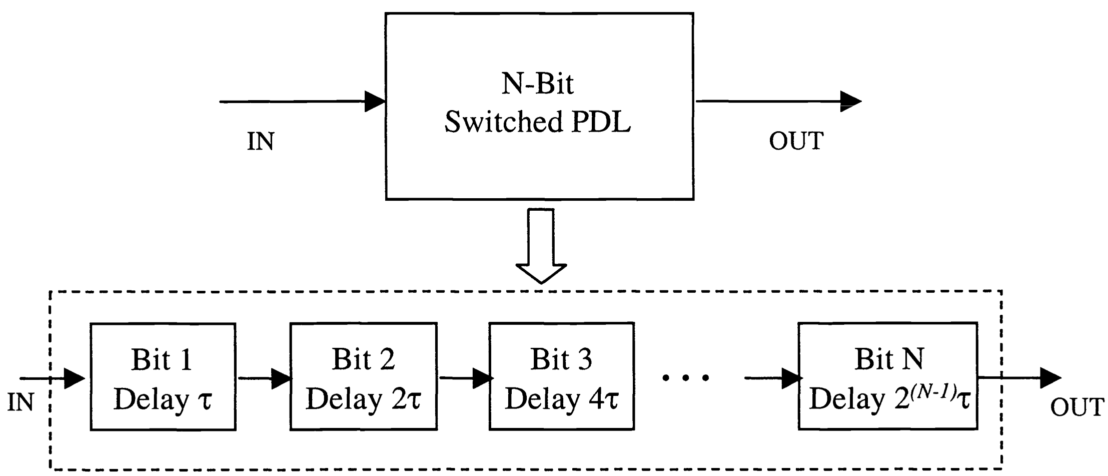

Fig.5 The proposed digital switched approach to realize the high dynamic range PDL.

Fig.5 shows the classic N-bit switched binary PDL structure that we use to efficiently impart a large variety of time delays to the optical wavelengths. Via proper choice of the delay path lengths in each single bit module, for example, first bit delay τ, second bit delay 2τ, third bit delay 4τ, fourth bit delay 8τ, …., and finally, Nth bit delay $2^{N-1}\ \tau$, 2^{N-1} independent delays with τ increment can be generated upto a maximum time delay of $2^{N}\ \tau$. Hence, for N=10 bits, 1024 different time delays can be picked with a τ interval from τ to 1024τ, providing a very large time delay dynamic range for coding the wavelengths for O-CDMA. Recall here that τ is the bit duration in a digital bit stream.

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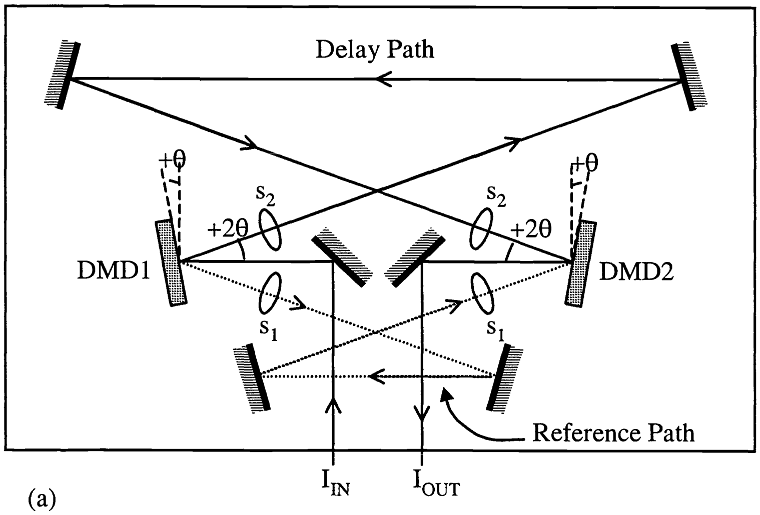
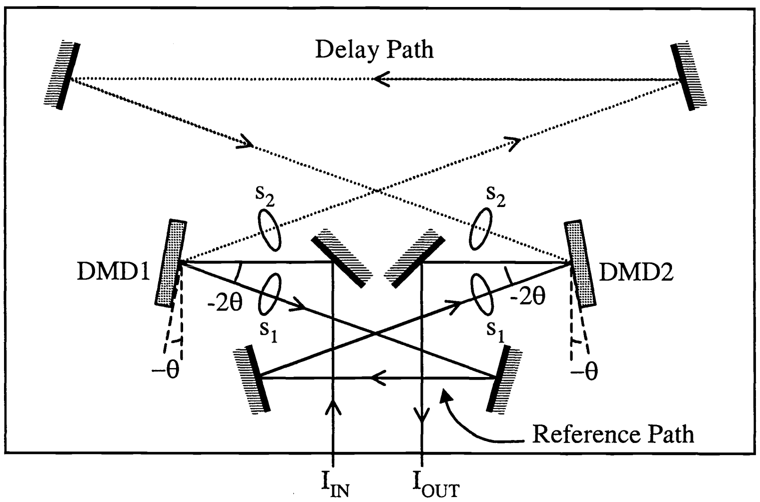


Delay Mode

(a)



Non-Delay Mode

(b)

Fig.6 The proposed single bit MEMS-based module used to realize the high dynamic range PDL and hence the MEMS O-CDMA encoder/decoder structure. (a) shows the delay and (b) shows the no-delay settings of the module for a simple case of all wavelengths following the same setting.

Fig.6 shows the top view of the proposed 2-D DMD-based encoder/decoder bit hardware. Light enters as the 2-D wavelength-space map I_{in} and exits as an imaged but processed 2-D wavelength-space map I_{out} that feeds the next single bit module. Input light can follows two independent paths in the structure where the paths have a relative time delay, e.g., 2^{n-1} τ for the nth module. For a given path, light strikes four fixed mirrors and two digital tilt state mode DMDs labeled DMD1 and DMD2. Each DMD has nearly a million 1-D tilt micromirrors where each mirror can be set to a + θ° or – θ ° state. The choice of the mirror state in the two DMDs dictates which optical path the light wavelength selects. The choice of the number of micromirrors in the x-direction (or λ direction) selects the wavelength band slicing required for coding. Similarly, the choice of the number of micromirrors in the y-direction (or optical power direction) selects the power (or wavelength time delay replica) slicing required for coding. Since the typical DMD has a 1000 x 1000 mirror count, there is enormous bandwidth for OCDMA wavelength and power coding.

Note that within each bit module, different wavelength spatial packets can be programmed independently via independent mirror control of the DMDs. Both DMDs operate with the same spatial control mappings so as to preserving

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the spatial slicings between the module input and output ports. Typically the angle θ is 9.2 degrees for the TI DMDs and the switching speed of each micromirror is 15 microseconds. This is fast in comparison to 10 ms for typical infrared NLCs. It is very important to note that TI has optimized many aspects of the DMD for infrared operations at 1550 nm. For instance, total loss for the TI DMD is now around 1.7 dB, including fill factor, diffraction, and IR window loss. Thus, the new TI DMD forms a low loss component that is practical to use for our cascaded MEMS-based O-CDMA encoder/decoder designs.

Also note that imaging lenses S's have been used in the paths as these are critical to maintain the spatial allocations of the input wavelength-space 2-D maps "I" as they travel through module. The placement of these imaging optics can be further optimized to reduce size and improve imaging input/output conditions.

To get an idea for the delay values and sizes, we use the example for 10 Gbps that then gives a τ of 0.1 ns that corresponds to a 3 cm delay in freespace or a 2 cm delay in a glass solid optic block. For a practical module implementation, consider a 6-bit encoder, implying that the most significant bit (MSB) delay for the 6^{th} bit module is 32x2 cm=64 cm. Since the delays are designed as loops, this 64 cm can be evenly distributed in symmetrical ways, thus reducing overall module size to form compact structures. Folding geometries can also be deployed to reduce size. Recall that we are implementing high spatial density parallel processing, so the choice of fiber arrays is not practical when using SMFs and when flexibility is required for how wavelengths and optical power are sliced. Furthermore, the next data standard is a much faster 40 Gbps; hence delay lengths in the future will be reduced by another factor of four, making our hybrid OCDMA modules even smaller.

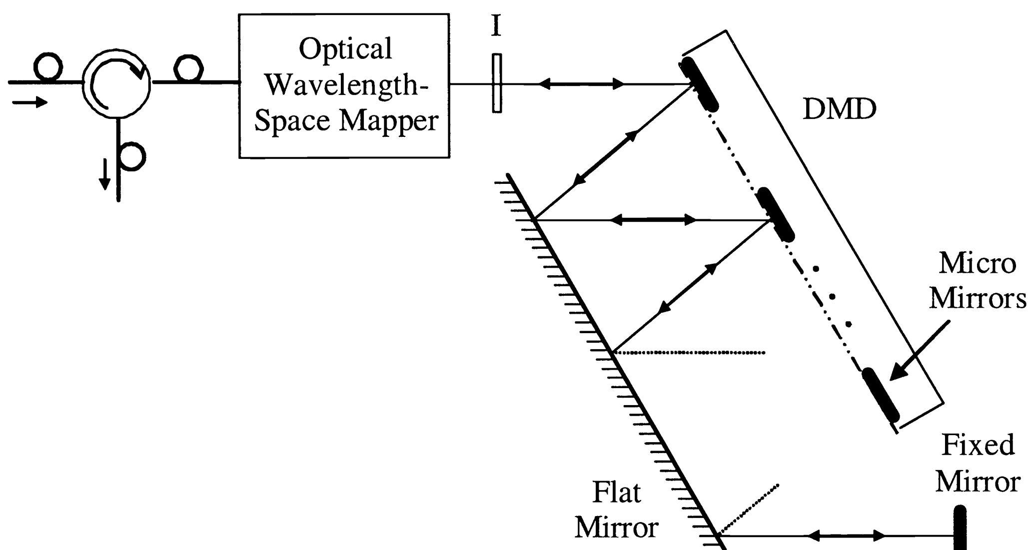

Fig.7 (a) An alternative moderate time delay dynamic range MEMS-based O-CDMA encoder/decoder design using one 2-D DMD in parallel with a fixed mirror. (Shown for simplicity in top view)

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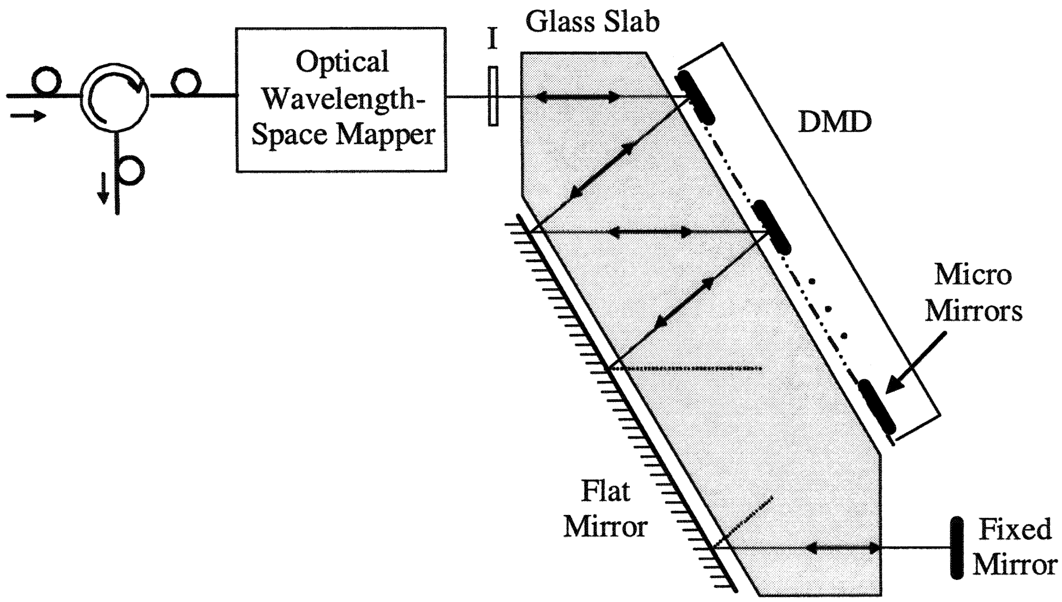

7 (b) An alternative MEMS-based O-CDMA encoder/decoder design of the Fig.7(a) design. Shown is the use of a glass slab to increase path lengths for longer time delays.

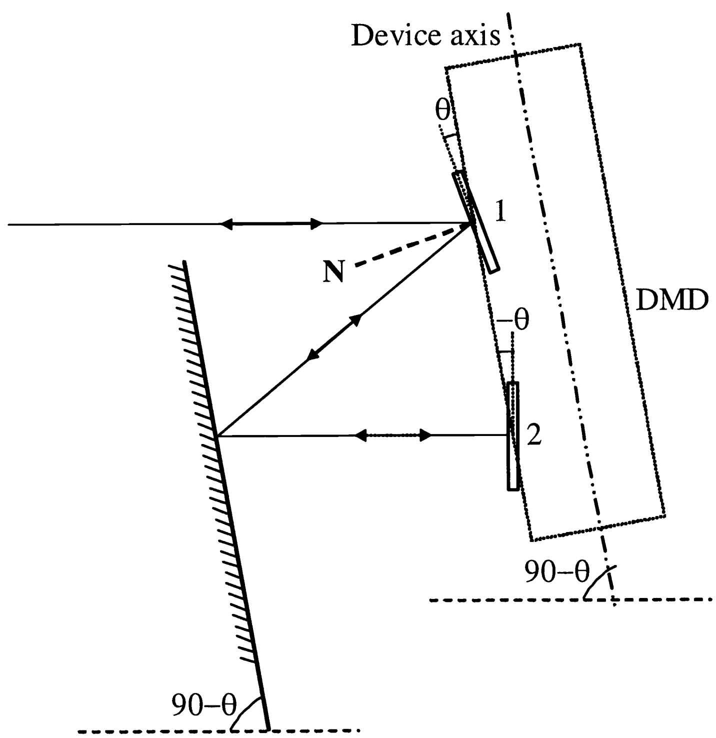

Fig.7 (c) An alternative MEMS-based O-CDMA encoder/decoder design of the Fig.7(a) design. Shown is the orientation of the micromirrors for proper module operations.

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Although the binary switched MEMS-based O-CDMA encoder design is an efficient way to get high dynamic range coding, certain communication scenarios can do with a smaller more moderate dynamic range (e.g., 10τ) time coding of data. In this case, Fig.7(a)-(c) shows an alternative MEMS-based O-CDMA encoder/decoder design using two parallel mirrors where one mirror is the reconfigurable 2-D DMD. Broadband data modulated light enter via an optical circulator and first passes through a lens-grating based optical wavelength-space mapper (as shown earlier in Figure 3). The generated 2-D wavelength-space map "I" enters the two DMD serial PDL. Again, the number and location of the micromirrors on the DMD controls the wavelength and power slicing of the broadband light. In addition, again the binary tilt state of the micromirrors determines whether the light retroreflects and returns back to the circulator or continues traveling through the PDL to acquire larger delays. Because of 1.7 dB insertion loss per DMD reflection, losses can add up fast and hence a maximum of 10 bounces on DMD or near 17 dB loss module is recommended (last bounce is off a fixed regular mirror). In this case, the delays can be approximately given by τ, 2τ,$3\tilde{\tau}$,.., 10τ based on ray-optics optical path design. Note that a glass block can be placed between the fixed parallel mirror and DMD to increase optical time delays. Also note that as θ is a rather large 9.2 degrees for the IR TI DMD, larger delays can be imparted if the distance between the mirror and DMD is increased and imaging lenses are used between the mirror-DMD planes. Hence, there is some flexibility and usefulness of the Fig.7 design when only moderate time delays are required for O-CDMA.

The second part of this paper is to combine our previously proposed spatial O-CDMA technique with the first proposed hybrid encoder/decoder for fiber O-CDMA to demonstrate freespace O-CDMA communications with a two level security system. The basic hybrid spatial-fiber O-CDMA approach is shown in Fig.8. The basic idea shown in Fig.8 involves first using the fiber-optic hybrid LC-MEMS encoder for imparting the multi-dimensional O-CDMA code on the given user data signal. Next, light from the encoder is expanded and collimated in freespace and imparted a 2-D image code on the freespace transmitter beam. This encoded beam travels the freespace distance and strikes a freespace receiver made up for several spatially distributed sampling heads that each feed a hybrid LC-MEMS fiber O-CDMA decoder. The electrical signals from the array of decoders is split and partly distributed to a spatial data signal processor (called SPC) with the other part of the splitter signals sent to an electrical combiner. When the spatial data signal processor indicates a spatial correlation with a stored user spatial code, the combiner is triggered to output the combined signal that is ready for thresholding and gives the desired user data. Thus, in order for the freespace link to perform securely, first correct fiber-optic O-CDMA decoding is required and then proper spatial O-CDMA decoding is required, forming a 2-level high security link.

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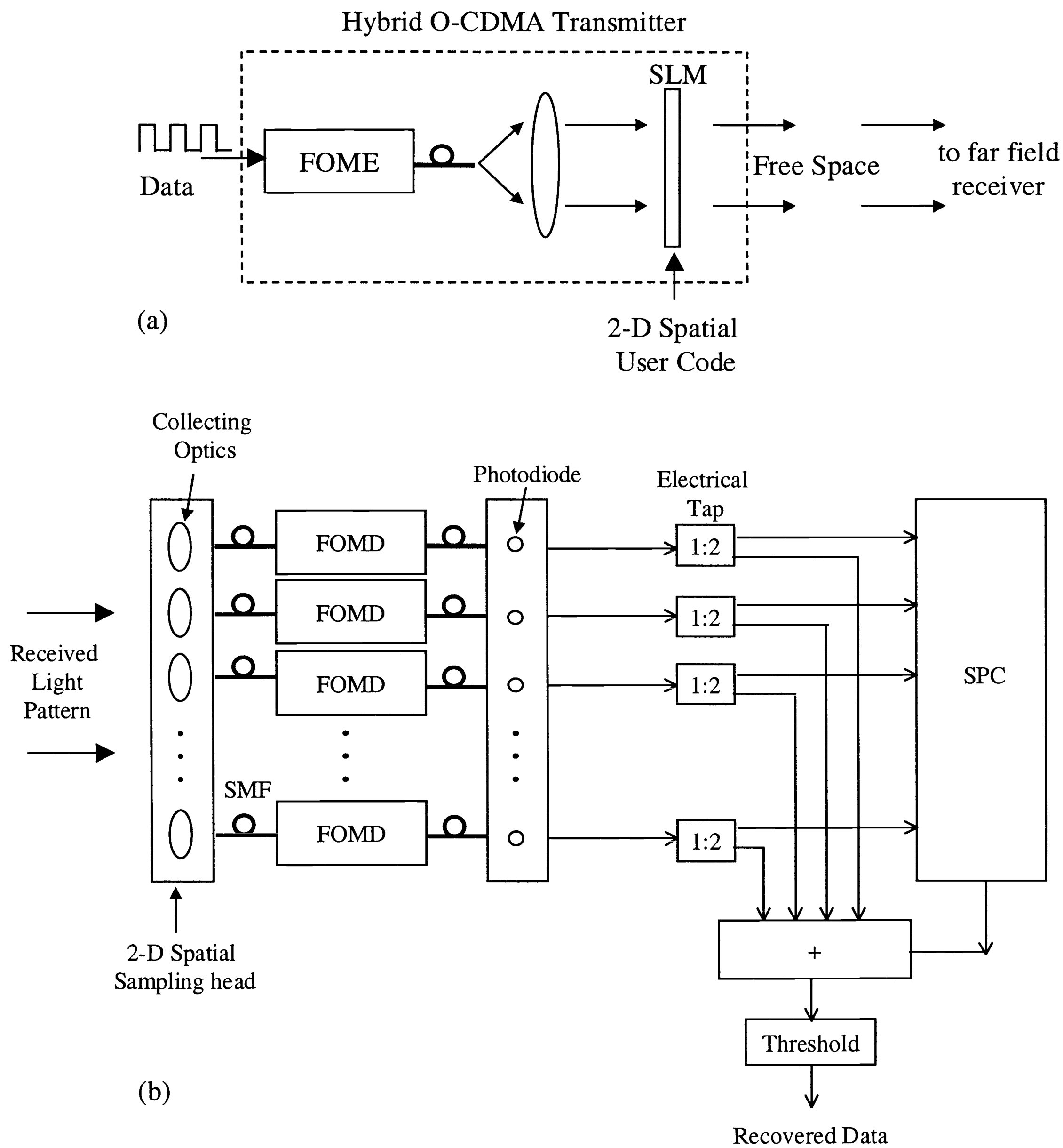

Fig.8 The basic hybrid spatial-fiber O-CDMA approach for two level security freespace communications O-CDMA. FOME: Fiber-Optic Multidimensional Encoder; FOMD: Fiber-Optic Multidimensional Decoder; SPC: Spatial Processing Correlator.

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