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(54) **Title:** HIGH PERFORMANCE SPECTRAL DATA STORAGE SYSTEM

(57) **Abstract:** A system and method to spectrally store data in a spectrally addressable hole-burning material (16), such as an Eu (Europium)-doped YSO (Yttrium Silicate) crystal. The digital data to be spectrally stored is first converted into an RF (radio frequency) form by modulating the data using multiple RF frequencies, with each RF frequency carrying one of the data bits. The RF-encoded data is then optically modulated by an electro-optic modulator (12) using one or more laser frequencies as carriers. The optically modulated output is sent to a beam router (14) that projects the output onto a predetermined location or spot on the storage material. The hole-burning material (16) is shaped as an array of waveguides to combat light diffraction and maintain high spatial storage density. The stored data is read using a high speed detector (18) along with a bank of RF filters (20). The use of laser tuning together with parallel RF modulation allows access to the full inhomogeneous spectrum of the hole-burning material (16) storing the data. The addressing of the data storage locations is massless, i.e., it does not involve any moving parts.

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HIGH PERFORMANCE SPECTRAL DATA STORAGE SYSTEM

REFERENCE TO RELATED APPLICATIONS

This application claims priority benefits of prior filed co-pending United States provisional patent application Serial No. 60/308,128, filed on July 30, 2001, the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

Field of the Invention

The present invention generally relates to data storage systems and methods, and, more particularly, to a data storage system that spectrally stores data on a hole-burning material using a physical motionless addressing mechanism.

Description of Related Art

Conventional data storage systems utilize two spatial dimensions. For example, electronic DRAM (Dynamic Random Access Memory) stores data on the 2D (two dimensional) surface of a silicon chip, whereas magnetic Hard Disc (HD) uses the 2D surface of a magnetic medium. As a result of this conventional 2D approach, physical motion (e.g., disc rotation) is required in order to achieve high capacity. The necessity of physical motion results in large access latency (i.e., the time it takes for the memory to store or retrieve data), producing a computational bottleneck in memory intensive applications such as scientific computing, database management, audio/video intensive environments, and numerous network services.

Semiconductor storage technologies (e.g., SRAM (Static Random Access Memory), DRAM, etc.) achieve latencies of a few nanoseconds and capacities of a few hundred megabits per unit. High capacity is achieved by combining individual storage units. Near the other end of the memory hierarchy, magnetic hard disc (HD) technology offers a high capacity solution at a very low cost; however, the data latency rises to the range of a few milliseconds owing to the need for disc rotation. The fundamental limit on data density on an HD is predicted at 100 Gbit/in^2 (i.e., the supraparamagnetic limit) and the latencies are predicted to be greater than 1 ms, limited by the precision mechanical systems that access data in disc-based implementations. Numerous efforts are aimed at beating these limits and include optically assisted magnetics, SQUID (Superconducting Quantum Interference Device)-based readout, and atomic-scale storage; however, none of these approaches can mitigate the slow access of a disc-based solution. Recent attempts to extend the capabilities of mass storage systems at this disc-based end of the memory hierarchy have focused on the capabilities of 3D technologies.

There are numerous potential 3D storage technologies including multilayer optical disks and semiconductor chip stacks. Throughout the past 10 years, there has been active interest in volume holographic optical storage with a significant investment in supporting materials and devices. Recent efforts include government funded consortia as well as startup efforts. Mature holographic demonstrators have shown the feasibility of low capacity (1 Gbit) low read-latency (10 μs) ROM (Read Only Memory) solutions in $LiNbO_3$ (Lithium Niobate) as well as moderate capacity (10 Gbit) high latency (1 ms) WORM (Write-Once Read-Many) solutions in a polymer-disk-based system. The main limitations of these holographic implementations are that: (a) both systems suffer from poor capacity/power scaling owing to the shared use of material dynamic range (i.e., the so-called $1/M^2$ loss as discussed in more detail in the article titled "System Metric for Holographic Memory Systems," by Mok, Fai H., Geoffrey W. Burr, and Demetri Psaltis, Optics Letters, Vol. 21, No. 12, pp. 896-898, June 15, 1996, the disclosure of which is incorporated herein in its entirety), (b) the low recording sensitivity in $LiNbO_3$ produces a large read-write asymmetry (a factor of thousands), and (c) the limited thickness in polymer-based implementations requires mechanical motion to obtain acceptable storage capacities.

Optical data storage using hole-burning materials has also been proposed and since the time it was proposed 10 years ago, numerous efforts toward hole-burning storage applications have been pursued. Benchtop demonstrations of hole-burning memory have been performed in both time-domain and spectral-domain architectures; however, none of these have achieved commercially competitive capacities, latencies, and data rates.

Spectral hole-burning is the adopted name for optical saturation of select spectral components of an atomic or molecular absorption spectrum. At low temperatures (generally below 10^0 Kelvin), certain rare earth atoms/ions or organic chromophores incorporated as dopants into appropriate host matrices exhibit absorption spectra that are inhomogeneously broadened. At low temperature (below 10^0 Kelvin (preferably between 4^0- 6^0 Kelvin)), the natural absorption linewidth in these species remains un-broadened to any appreciable extent by random perturbations induced by phonons or by magnetic dipole spin-flips. It is noted that, at higher temperatures, phonons interact with the electronic transitions in dopant ions, with the impact that such transitions broaden the absorption linewidth for each ion, which is not preferable. Concurrently the host environment, through the influence of local inter-molecular fields, shifts the absorption line centers for individual dopant absorbers into a Gaussian spectral distribution whose width exceeds that of a single absorber by a factor of approximately one million in many dopant-host systems. This aggregate absorption profile is called an inhomogeneous spectrum; each of the spectrally much narrower constituents (i.e., the narrower linewidth at low temperature) is called a homogeneous spectrum. Narrow-spectrum laser illumination of some spatial location of such a material bleaches the absorption of a select, resonant, homogeneous linewidth. This bleaching persists for at least the excited state lifetime of the dopant; in many materials a mechanism exists for providing persistence of the bleached population well beyond that duration, in some cases for up to several days. Subsequent spectral probing of the inhomogeneous spectrum reveals dips in the absorption spectrum at these formerly bleached spectral locations. These appear as 'holes' in the overall absorption profile, hence the name.

The main limitations plaguing previous time-domain efforts to optically store data using hole-burning materials include the need for advanced laser technology, the cost of high speed modulators and detectors, and the concomitant burden of high speed interface complexity. In addition, the time-domain approach uses temporal holography and therefore suffers from a resource sharing cost similar to that plaguing spatial holography, manifesting itself as low data recall efficiency and crosstalk noise. On the other hand, previous spectral-domain solutions have failed to identify a unified system approach that realizes high storage capacity and low latency with an acceptable device-complexity cost. Serious attention has not yet been paid to important system issues such as data fidelity, interface requirements, or the position that such a high-capacity, low latency device would occupy within the memory hierarchy.

It is therefore desirable to devise a data storage system using hole-burning materials that addresses the foregoing storage capacity and latency issues without sacrificing data fidelity or complicating the interface requirements. It is also desirable to avoid the problems of shared resources (such as in photorefractive memories) and the read/write asymmetry (found in, for example, the $LiNbO_3$ system), while achieving a commercially competitive set of overall system specifications (e.g., high capacity of > 10 Gbits per unit, low access latency of < 10 μs, etc.) for the data storage system. It is further desirable to devise the data storage system without moving parts to address the storage locations for data storage or retrieval.

SUMMARY

In one embodiment, the present invention contemplates a system for spectrally storing data in a hole-burning material, where the data to be stored includes a plurality of data bits and an optical spectrum of the hole-burning material has an inhomogeneous linewidth that is constituted of a plurality of homogeneous linewidths. The system comprises an electro-optic (EO) modulator configured to receive an RF (Radio Frequency)-encoded data signal as a first input and a laser signal as a second input, wherein the RF-encoded data signal contains the plurality of data bits in an RF form, and wherein the EO modulator optically modulates the RF-encoded data signal using the laser signal as a carrier signal, thereby generating an optically modulated output; and a beam router optically coupled to the EO modulator to receive the optically modulated output therefrom and thereafter to project the optically modulated output onto the hole-burning material to spectrally record the data therein.

The hole-burning material may be an Eu (Europium)-doped YSO (Yttrium Silicate) crystal. In one embodiment, the beam router is formed with a plurality of MEMS (microelectromechanical systems) micro-mirrors, where each of the plurality of micro-mirrors is electrically addressable individually to project the optically modulated output onto a corresponding x-y location on the hole-burning material. In another embodiment, the hole-burning material that stores the data is patterned in the form of a plurality of waveguides supported by a low optical refractive index supporting material.

When reading the spectrally stored data, the appropriate location or "spot" on the hole-burning material is illuminated with a fully modulated optical signal and the light emanating from the illumination is focused on a high speed detector via a focusing lens. The high speed detector first converts the illuminated light output from the hole-burning material into an equivalent electrical signal and then demodulates the electrical signal to generate its constituent RF baseband signals. Each RF baseband signal contains one of the stored data bits in the RF form. The RF baseband signals are then filtered using a bank of RF filters to extract the data bits therefrom.

In one embodiment, the present invention contemplates a method of spectrally storing data in a hole-burning material. The method comprises receiving an RF-encoded data signal containing the data in an RF form; optically modulating the RF-encoded data signal using a laser beam as a carrier, thereby generating an optically modulated output; and routing the optically modulated output to a predetermined location on the hole-burning material.

In another embodiment, the present invention also contemplates a method of reading data spectrally stored at a location on a hole-burning material. The method comprises optically modulating an RF-encoded data signal using a laser beam as a carrier, wherein the RF-encoded data signal contains a plurality of data bits in an RF form and wherein each of the plurality of data bits has an identical value, thereby generating a fully modulated laser beam; illuminating the location with the fully modulated laser beam; detecting an optical output emanating from the illuminated location; and retrieving the data from the detected optical output.

In a still further embodiment, the present invention contemplates a system and method of forming a memory unit, where the memory unit comprises a plurality of waveguides, wherein each of the plurality of waveguides is formed of a hole-burning material to spectrally store data therein; and a support medium having a low optical refractive index, wherein the support medium physically separates each waveguide in the plurality of waveguides and provides a supporting layer for said plurality of waveguides.

The spectral data storage system according to the present invention utilizes spectrally addressable materials in a novel high-capacity (> 10 Gbits) configuration that offers very low access latency (< 10μs) and fills an important niche in the computer memory hierarchy between DRAM and magnetic disc. The use of laser tuning together with parallel RF modulation allows access to the full inhomogeneous spectrum of the spectrally addressable hole-burning material storing the data. Three forms of massless (i.e., no moving parts) addressing—parallel RF modulation, laser tuning, and spatial routing—are used to achieve high data storage capacity and low latency.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification, illustrate embodiments of the invention that together with the description serve to explain the principles of the invention. In the drawings:

Fig. 1 illustrates an exemplary spectral data storage system according to one embodiment of the present invention that stores data using a hole-burning material;

Fig. 2 is a simplified depiction of spectral data organization using laser tuning in combination with RF encoding in the storage system of Fig. 1;

Fig. 3 depicts an exemplary waveguide pattern for the patterned media shown in the data storage system of Fig. 1;

Fig. 4 illustrates an exemplary MEMS-based micro-mirror array for the beam router shown in the data storage system of Fig. 1; and

Fig. 5 shows graphs of experimental results obtained through measurements of a three-channel write-read process using a hole-burning material according to one embodiment of the present invention.

DETAILED DESCRIPTION

Reference will now be made in detail to the preferred embodiments of the present invention, examples of which are illustrated in the accompanying drawings. It is to be understood that the figures and descriptions of the present invention included herein illustrate and describe elements that are of particular relevance to the present invention, while eliminating, for purposes of clarity, other elements found in typical data storage systems or networks.

It is worthy to note that any reference in the specification to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. The appearances of the phrase " in one embodiment" at various places in the specification do not necessarily all refer to the same embodiment.

Fig. 1 illustrates an exemplary spectral data storage system 10 according to one embodiment of the present invention that stores data using a hole-burning material 16. In one embodiment, the hole-burning material is an Eu (Europium)-doped YSO (Yttrium Silicate, Y_2SiO_5) crystal. Other host materials for the hole-burning memory 16 may include, for example, $LiNbO_3$ (Lithium Niobate), Y_2O_3 (Yttrium Oxide), Barium Titanate, GaAs (Gallium Arsenide), and KTP (Potassium Titanyl Phosphate). Other dopants may include Pr (Praseodymium), Er (Erbium) and Eu. As shown in Fig. 1, the data storage system 10 includes an electro-optic (EO) modulator 12, a beam router 14, a patterned media 16 containing the hole-burning material, a focusing lens 17, a high speed detector 18, and a bank of RF (Radio Frequency) filters 20. An RF-encoded data signal input to the EO modulator 12 is modulated by the EO modulator 12 using a laser signal as a carrier signal and the modulated optical output from the EO modulator 12 is routed using the beam router 14 and projected onto the patterned media 16 (i.e., the hole-burning material) to spectrally store the data contained in the RF-encoded input. When reading the stored data, the light output from the hole-burning material 16 is sensed and demodulated by the high speed detector 18 and thereafter filtered by the bank of RF filters 20 to generate the original digital data bits.

It is noted that the terms "patterned media" and "hole-burning material" are used interchangeably in the discussion given herein (as noted hereinbelow, material patterning is not a requirement to carry out the teachings of the present invention). Thus, the same reference numeral "16" is used to refer to either or both of them, depending on the context. Further, some of the desirable properties or attributes for a spectral hole burning material to support the use of the hole-burning material in a random access memory include: (1) High oscillator strength that is as large as allowed by specified data hole width, so that the homogeneous linewidth equals one half the data hole width. (2) The branching ratio be as large as possible, preferably exceeding 1:2 (i.e. 50% or even 99%). The branching ratio indicates the proportion of the atomic population that relaxes into its original ground state configuration vs. the fraction that relaxes to other configurations. In the Eu:YSO system, these configurations comprise three ground state hyperfine energy levels. (3) The inhomogeneous linewidth exceeding 10,000 times the homogeneous linewidth. (4) Persistence: At the theoretical minimum, the persistence should exceed the population relaxation time plus twice the time equal to the inverse of the data spectral hole width multiplied by the linewidth ratio. That is, $T_P > T_1 + 2 \times (1/\Delta\nu_{hole}) \times (\Delta\nu_{inhomo}/\Delta\nu_{homo})$. Here, T_P represents the persistence time, T_1 represents the excited state lifetime for the active ion species, and $\Delta\nu_{hole}$ represents the linewidth of the spectral hole that represents data (its minimum width equals twice $\Delta\nu_{homo}$, but it can be chosen orders of magnitude greater to reduce memory access latency – generally at the expense of optical power). The expression $(\Delta\nu_{inhomo}/\Delta\nu_{homo})$ is termed the linewidth ratio. It is the ratio of the total absorption linewidth (called the inhomogeneous line) to its constituent spectral components (the homogeneous lines). This ratio indicates the maximum number of spectral components available to store data. Random access implies that persistence be longer than this by a large factor – at least a factor equal to the linewidth ratio. (5) Hyperfine splittings of any level should be nearly equal. Difference between the values of the hyperfine splittings of the two main levels should be large. (6) Host should have one ion site, with low magnetic dipole moment. Oscillator strength is independent of optical propagation direction or polarization. (7) One rare earth isotope. (8) Low propensity for exhibiting (especially instantaneous) spectral diffusion. (9) Flat inhomogeneous spectrum to obviate frequency channel equalization.

The optical data storage system in Fig. 1 uses an optically addressable material (i.e., the hole-burning material 16) whose response is spectrally selective. The use of spectrally addressable storage material replaces physical motion (e.g., disc rotation in the prior art magnetic hard drives) by massless spectral addressing, thus dramatically reducing readout latency with no adverse impact on storage capacity. The storage system architecture 10 shown in Fig. 1 is a spot-wise (as opposed to page-wise) storage system architecture, meaning that the data storage and retrieval is performed on a spot-by-spot basis using the per-spot storage capacity in the hole-burning material 16.

It is noted that three forms of massless (i.e., no moving parts) addressing— parallel RF encoding, laser tuning, and spatial routing— are used in the embodiment shown in Fig. 1 to achieve high storage capacity and low latency. Fig. 1 depicts the use of multiple spatial locations (on the hole-burning material 16) in which each location is defined by a waveguide (in the patterned media 16) that facilitates the required material interaction length. Beam routing among these spatial locations is achieved through the use of silicon microelectromechanical (MEM) actuators (in the beam router 14) in which row and column micromirrors are actuated to deflect an incident beam to a specific xy address. There are five key elements in the data storage system 10 shown in Fig. 1: (1) RF encoding, (2) laser tuning, (3) material patterning, (4) beam routing, and (5) system integration. Each of these elements is now described in more detail hereinbelow.

RF Encoding

The homogeneous linewidths (often in the range of 1 kHz to 1 MHz (e.g., < 10 kHz in one embodiment), although values outside this range are acceptable) of the hole-burning storage material 16 facilitate access to a portion of the storage material's per-spot capacity via RF encoding or modulation. Through RF encoding fully parallel reading and writing can take place within the electronic domain, eliminating the need for sophisticated optical components such as spatial light modulators and high-speed cameras. For example, using a system latency specification of L=1 μs, an effective spectral resolution of 1 MHz can be obtained. A data rate specification (in bits per second) of R=100 Mbps results in a required spectral parallelism of N_{RF} =100 and a 100 MHz RF encoding bandwidth. In general, RF parallelism is related to memory latency and required data rate as N_{RF} =LR, for values of latency shorter than the homogeneous lifetime $T_H=1/\Delta\nu_H$, where $\Delta\nu_H$ is the homogeneous spectral linewidth.

Fig. 2 is a simplified depiction of spectral data organization using laser tuning in combination with RF encoding in the storage system of Fig. 1. As shown in Fig. 2, the spectral resource offered by the hole-burning material 16 is utilized when laser tuning is used along with parallel RF encoding to access the full inhomogeneous spectrum of the, e.g., Eu-doped YSO crystal. As shown in Fig. 2, the data bits are RF-encoded or modulated onto a predetermined set of RF frequencies as a first set of carrier signals and then modulated onto one or more predetermined laser frequencies as a second set of carrier signals so that the final data-carrying frequencies lie within the 10GHz inhomogeneous linewidth of the, e.g., Eu-YSO crystal. As discussed later hereinbelow, the frequencies in the final modulated signal may lie above and below the carrier laser frequency (as indicated by the RF sidebands in Fig. 2). It is noted that the term "RF encoding" is used herein to refer to RF modulation, i.e., modulation of a digital signal using an RF signal as a carrier.

Each data-bit carrying laser modulated signal (here, each of those signals in the laser modulated output from the EO modulator 12 that contain the "1" bit) illuminates a spatial location in the hole-burning material 16 to spectrally store the "1" bit as a "hole" at that location's homogeneous linewidth. As discussed hereinbefore (in the Background section), the subsequent spectral probing of the inhomogeneous spectrum reveals these "holes", thereby allowing the stored data to be retrieved.

As can be seen from Fig. 2, there may be multiple (e.g., as many as 1000) distinct RF frequencies (represented by the term "m ω_0" in the discussion of the input signal $S_{in}(t)$ given hereinbelow) simultaneously imposed onto an optical carrier. RF source generators often provide a multiplicity of tones or RF signals that are in phase. That is, periodically, all of these RF tones attain the peak of their sinusoidal amplitudes simultaneously. This peaking feature causes the instantaneous signal amplitude (and power) of the signal combining all RF tones to attain high value (on the order of 1000 times the single-tone amplitude excursion). High amplitude can saturate downstream amplifier and modulator components and compress the accessible dynamic range of these components as well as require substantially greater optical power for acceptable storage performance. Therefore, to circumvent this problem of peak power saturation, the phases of the constituent RF tones may be randomized. The impact of this randomization may be more significant for a greater number of tones since the likelihood of the peak power converging to the mean increases. A gradient descent algorithm may be applied to any combination of RF tones to calculate the optimal selection of relative phases in suppressing peak power excursions.

In the discussion above, the RF tones representing the digital word or data are consecutive across the absorption spectrum. However, in an alternative embodiment, the tones representing the bits of a digital word may be regularly distributed (or even deterministically randomly distributed) at wide intervals across the absorption spectrum. For example, rather than occupying eight consecutive spectral positions separated by 100 KHz within a spectral absorption band of 800 KHz (100 KHz x 8 = 800 KHz), every bit in an 8-bit data word may occupy every 100th spectral position on a 10 MHz grid (100 x 100 KHz = 10 MHz) extending over an 80 MHz spectrum. In this case, 100 other 8-bit data words could be interleaved within the entire spectral range. This interleaving approach may allow flexibility in hardware design—i.e., the allocation of laser frequencies and RF frequencies—and may also suppress crosstalk between neighboring spectral channels.

In one embodiment, the EO modulator 12 may include the low-cost circuitry and drivers necessary to perform the required RF encoding. In that case, the EO modulator 12 receives the data to be stored in a digital form and thereafter performs the necessary RF encoding on the received data to convert the digital data into RF signals to be modulated using a laser carrier. In another embodiment, a more compact waveguide-based EO modulator may also be used.

The recording power requirements for the system 10 shown in Fig. 1 may be estimated in the case of fully incoherent RF encoding. This scheme offers the best utilization of average optical power and can be achieved through the use of an RF phase mask (analogous to the spatial phase masks used in Fourier transform holographic storage). The modulating RF signal (i.e., the spectral data input to the EO modulator 12) can be written as $S_{in}(t) = \frac{1}{2} + A \Sigma d_m \cos(m\omega_0 t+\phi_m)$, where ω_0 represents the RF channel spacing (1 MHz in the example shown in Fig. 2), d_m represents 1's and 0's in the N_{RF} =100 data bits to be recorded (d_m=0 or d_m=1), ϕ_m are a set of random phases, selected to produce a nearly uniform power spectrum for $S_{in}(t)$, and A is a normalization factor. Using such an encoding, an estimated worst case power requirement of 640 mW in a 10 μm diameter recording spot can be obtained.

Recording with $S_{in}(t)$ as defined above results in a collection of holes whose spectral locations are defined by the collection of frequencies $\omega_{laser} \pm m\, \omega_0$ for all values of m at which d_m=1. This is illustrated in Fig. 2 by the "RF sidebands" in the modulated signal above and below the laser carrier frequency, ω_{laser}.

Readout of the RF-encoded spectral memory is accomplished by illuminating an appropriate storage location or "spot" in the memory (i.e., the hole-burning material 16) with a fully modulated beam (i.e., d_m=1 for all m (all data bits have an identical value)). For those frequencies at which recording has taken place (i.e., frequencies at which there are holes), a strong RF spectral component is present in the output whereas other frequencies will produce strong absorption and a small readout signal. The optical readout signal emanated from the illuminated spot is focused on the high speed detector 18 by the focusing lens 17. The use of the focusing lens 17 allows focusing the readout signals from all the storage locations (or waveguides as discussed later hereinbelow) on the detector 18. In one embodiment, the high speed detector 18 may include an opto-electric transducer (e.g., a photo diode or any other photodetector) (not shown) to sense the optical output from the memory 16 and convert the sensed output into an equivalent electrical signal or current. A detector circuit (not shown) in the high speed detector 18 may then demodulate the data-bearing electrical signal into a group of RF baseband signals carrying the data bits read from the hole-burning material 16. In one embodiment, the detector 18 performs a homodyne detection that shifts the spectral signals (output from the memory 16) to RF baseband signals. Each RF filter in the bank or array of RF filters 20 operates on a corresponding RF baseband signal to produce the desired data output bit in the digital form. The entire output from the bank of RF filters 20 constitutes the data word read from the memory 16. The output data (from the RF filters 20) can be written as $\hat{d}_m = \eta_m d_m + n_m$, where η_m represents the contrast ratio of the retrieved spectral data and n_m represents noise sources that corrupt the output signal.

The relative benefits of various RF encoding options may be evaluated by the system designer in terms of signal fidelity (i.e., η_m and n_m) and implementational cost. For example, RF amplitude- versus phase-modulation may be evaluated in the presence of various noise sources such as detector thermal noise and material noise arising from side holes and anti-holes. Because of the complex structure of the energy levels of, e.g., Eu in YSO, burning a spectral hole via depletion of the population of one ground state hyperfine energy level introduces ancillary spectral features. These features assume the appearance of depleted or enhanced absorption at other (deterministic) frequencies called side holes and anti-holes, respectively. The use of single- versus dual-sideband encoding formats may also be evaluated as well as heterodyne versus homodyne detection. RF phase mask technologies may also be studied. Guard bands may be used at regular intervals across the inhomogeneous linewidth to separate spectral regions in which the stored bits would be discernible from those in which the bits may get obscured by the ancillary spectral features that arise during the exposure of a data-bearing spectral hole. The use of guard bands may enhance the SNR (signal-to-noise ratio) for data actually written into the spectrum and may also allow for erasure of segments of the optical spectrum without destroying data throughout the spectral range. The selection of appropriate models may then be made for an overall system design (for the storage system 10) that optimizes performance metrics such as capacity, power, and bit error rate.

Laser Tuning

The inhomogeneous linewidth (> 10 GHz) of the hole-burning storage material 16 is sufficient to achieve a large per spot storage capacity; however, access to this capacity using RF addressing alone would require high cost interface electronics. Therefore, as shown in Figs. 1 and 2, laser tuning is used along with RF encoding to relax the addressing requirements of the RF electronics while providing access to the full material capacity. In one embodiment, a tunable laser (not shown) outputting a cw (continuous wave) laser signal may be used. The tunable laser may provide a number of laser frequencies lying within the inhomogeneous linewidth of the hole-burning material 16 as illustrated in Fig. 2. Thus, the tunable laser technology may provide access to per spot capacities of roughly $L\Delta\nu_I/2$ ($\Delta\nu_I$ is the inhomogeneous spectral linewidth), where the latency L is assumed to be shorter then the homogeneous lifetime, which is called $T_H = 1/\Delta\nu_H$ ($\Delta\nu_H$ is the homogeneous spectral linewidth) and the laser is assumed to have adequate frequency stability. Because homodyne detection is used in one embodiment to readout the stored data, all readout electronics operate at baseband and are transparent to the laser tuning. In case of homodyne detection, the output from the high speed detector 18 may be given as $S_{out}(t) = |\exp(j\omega_{laser}t) + \exp(j\omega_{laser}t)\,\Sigma\,\eta_m \cos(m\omega_0 t)\,|^2$, which produces a term in the output current (from the detector 18) proportional to the desired signal $s(t) = \Sigma\,\eta_m \cos(m\omega_0 t)$, which upon filtering (by the RF filters 20) yields the output data signal.

It is desirable to employ a tunable laser with wavelength near 580 nm. In one embodiment, frequency doubling of 1160 nm semiconductor laser (e.g., an external cavity diode laser (ECDL)) may be used to obtain the 580 nm wavelength laser. Here, the ECDL diode's frequency can be doubled by using a nonlinear optical crystal in a bow-tie cavity design to accomplish the 580 nm wavelength. In another embodiment, a dye laser may be stabilized to obtain the 580 nm wavelength. Alternatively, a new solid-state laser having the desired 580 nm wavelength may be designed and fabricated to provide a compact source of laser signals. In one embodiment, a semiconductor laser emitting 605 nm light may be cooled to 77^0 Kelvin to emit light at 580 nm. Some desirable attributes of cooled semiconductor lasers are lower lasing threshold current, higher damage threshold optical power, and better emission stability because of the reduced presence of phonons and their scattering influence on optical linewidth and jitter.

In another embodiment, an array of vertical cavity surface emitting lasers (VCSELs) may be used to achieve the attributes mentioned in the previous paragraph. Since VCSELs often incorporate quantum confined semiconductor regions to promote efficient lasing, and since quantum confinement confers shorter wavelength emission, VCSELs represent a good source for 580 nm laser emission when cooled to around 77^0 Kelvin. An array of VCSELs can be fabricated using the techniques known in the art to emit a spatially rastered array of optical frequencies as discussed in more detail in C. J. Chang-Hasnian, M.W. Maeda, N. G. Stoffel, J. P. Harbison, L. T. Florez, and J. Jewell, "Surface Emitting Laser Arrays with Uniformly Separated Wavelengths," Electronics Letters, Vol. 26, No. 13, pp. 940-941, June 1990, the disclosure of which is incorporated herein in its entirety. This rastered frequency array results from careful control of the cavity lengths of the constituent VCSELs. At low temperature, the emission wavelength of these lasers is quite stable with respect to modulation across threshold (i.e., on-off modulation). An array of rastered-frequency VCSELs may be tuned to emit around 580 nm, with emission frequencies separated (in the manner shown, for example, in Fig. 2) by a value between 200 MHz and 2500 MHz.

Material Patterning

In the embodiment illustrated in Fig. 1, material patterning is used to realize optical waveguiding during storage and retrieval of data and can facilitate large storage densities without a sacrifice in data fidelity. This technique facilitates the use of mature, readily available Eu-YSO crystals, for example. It is noted that the term "waveguide," as used herein, refers to optical waveguides. It is further noted that material patterning, although preferred, is however not required to carry out the teachings of the present invention.

Material patterning is useful to combat light diffraction and maintain high spatial storage density in the system 10. It is noted that the 1% doping levels in existing Eu-YSO samples results in an integrated cross-section of 0.26 cm^{-2} and an associated absorption of roughly 3.3 cm^{-1}. Spectral holes that are burned in the Eu-YSO hole-burning material 16 can achieve substantial reduction in absorption resulting in adequate signal contrast for reliable data retrieval; however, interaction lengths greater than 1 mm are required in order to achieve this acceptable readout signal fidelity in the presence of noise. Although materials research may relax this constraint somewhat, it is expected that material patterning may be required in order to combat diffraction and maintain high spatial storage density in the system 10. Patterning can be viewed as a means to support recording/readout optical waveguiding. Also, patterning effectively decouples storage density from sample thickness. For example, without optical waveguiding, a 1 mm sample thickness (of the hole-burning material 16) may limit the area of a single storage location to no less than 100 μm diameter before crosstalk between locations becomes significant. Using a capacity per spot $C=L\Delta\nu_I=10^4$, a spatial density of only 1.3 bits per μm^2 can be achieved in such a system. With material patterning, however, 10 μm diameter optical waveguides can be used to increase this to a commercially competitive 127 bits per μm^2.

Fig. 3 depicts an exemplary waveguide pattern for the patterned media 16 shown in the data storage system of Fig. 1. As shown in Fig. 3, an array of cylindrical waveguides 22 may be formed out of the YSO substrate 24 of the hole-burning material 16. In one embodiment, the YSO substrate 24 may be milled to create the waveguide array. Each cylindrical waveguide 22 may have 0.1 mm (100 μm) diameter and 1 mm length. The array of waveguides 22 may also be formed by deep substrate etching of the YSO substrate 24, supporting the created waveguides 22 using a backfill layer 23 of a material (e.g., epoxy) having a low optical refractive index, and thereafter removing the non-etched portion of the substrate 24 to form a tubular waveguide structure for the patterned media 16. The etching of the Eu:YSO crystal may be performed using the known ICP-RIE (inductively coupled plasma - reactive ion etching) method. The waveguides may also be patterned on the YSO substrate 24 using CO_2 laser cutting (into the substrate 24) or fabrication of fiber bundles on the substrate 24. Other, non-cylindrical, waveguide configurations may also be employed. Further, waveguides may also be fabricated in other hosts including, for example, barium titanate, lithium niobate, or other similar semiconductors. Also, erbium or europium may be in-diffused in combination with rubidium to substitute potassium in KTP (potassium titanyl phosphate) to provide a suitable host material for waveguide configuration.

In the embodiment where the patterned media or the hole-burning material constitutes a group of waveguides, each waveguide acts as a storage "pixel" or "spot." In other words, for each data storage operation, the beam router 14 selects only one waveguide onto which the data-bearing laser signal is to be projected. Because of its long interaction length and smaller diameter, the waveguide formation prevents light diffraction during data storage and retrieval activities, further increasing the per-spot data packing density for the patterned media or hole-burning memory 16. Thus, in the embodiment shown in Fig. 1, the entire memory 16 is constituted of a set of waveguides formed from a hole-burning material (e.g., an Eu-YSO crystal).

It is noted that the storage capacity for the hole-burning material 16 may be increased in two ways. Additional gains in inhomogeneous bandwidth translate directly into additional capacity (and density); whereas, relaxing the system latency constraint also increases the capacity at the expense of increased RF parallelism and the associated power cost. Opportunities to increase $\Delta\nu_I$ include compositional doping or the use of non-crystalline hosts for the hole-burning material 16; whereas, increased doping levels will increase sensitivity and recorded signal fidelity. Thus, improvements in inhomogeneous linewidth, storage time, and doping levels (impacting recorded signal fidelity) may be considered for desired capacity-latency values.

Beam Routing

As noted hereinbefore, the storage architecture 10 in Fig. 1 is a spot-wise (as opposed to page-wise) storage system architecture. The use of RF addressing supports the parallelism required to achieve acceptable data rates so that the use of spatial parallelism, along with its high interface component cost, becomes unnecessary. Integrated beam routing is a compact method of addressing a large array of storage locations (within the hole-burning material 16).

Fig. 4 illustrates an exemplary MEMS (microelectromechanical systems)-based micro-mirror array for the beam router 14 shown in the data storage system of Fig. 1. Thus, in the embodiment of Fig. 1, the beam router 14 is a MEMS-based device in which a 2D (two dimensional) array of silicon micro-mirrors 30 is used to direct a data-bearing laser to one of N_{XY} spatial locations (e.g., waveguides as explained hereinabove) on the memory 16. In one embodiment, the micro-mirrors are formed on a silicon substrate 28 using MEMS techniques. The mirror pitch may be 10 microns and the array's response times may be sub-microseconds, thus facilitating the high spatial density and low access latency required in the spectrally addressed storage system 10. It is observed that the required beam routing chip may be located either inside or outside the cryostat containing the hole-burning material 16. If placed outside the cryostat, the addition of a lenslet array may be required to relay the deflected beams onto the correct storage material location. This approach may result in a slight reduction in spatial data storage density.

As depicted in Fig. 4, appropriate row and column micro-mirrors are actuated (using silicon MEMS actuators (not shown)) to deflect the incident modulated laser beam to a specific x-y address (i.e., a specific data storage spot on the hole-burning material 16). The deflection takes place in the direction that is perpendicular to the 2D plane of the micro-mirrors 30. That is, the optical beams are deflected in a third dimension. This results in a three-dimensional (3D) beam routing device 14. It is noted that instead of using the MEMS-based array shown in Fig. 4, in one embodiment, the spatial routing to direct the data-bearing optical beam to the desired spatial address may be performed using a 2D AO (Acousto Optics) scanning. This substitution may result in a less compact system design; however, commercially available AO devices may offer a latency specification that is acceptable to a system designer. Alternatively, electro-holography (E-H) techniques may be used to deflect optical beams in the third dimension, perpendicular to the plane of the E-H modulators (not shown), as well as in the two-dimensional plane of the E-H modulators. This allows arbitrary addressing of a 2D array of device channel locations from a single input location. Further, the three-dimensional E-H beam router or modulator may carry signals of bandwidth up to several hundred GHz modulated onto an optical beam carrier.

System Integration

System integration may involve such issues as compact cryostat design, heat load management, interface protocols and addressing, coding and signal processing, etc. For the data storage and retrieval using the architecture 10 shown in Fig. 1, high speed electronics may be required to provide parallel RF addressing and readout. These high-speed electronics may interface with advanced parallel signal processing and coding hardware to provide acceptable user bit error rate in the presence of noise and interference effects such as detector noise, scatter noise, spectral crosstalk, etc.

The following describes exemplary devices and specifications for a memory device or spectral storage system 10 that may be built using the near-term and COTS (Commercial Off-The Shelf) technologies.

1. The hole-burning material 16 may be Eu-YSO crystal with $\Delta\nu_I$=10 GHz resulting in a per spot capacity of 10^5 bits for a 10 μs latency. Patterning may be performed by either photolithographic etching, mechanical milling or laser machining of 100 μm diameter rods. A 64X64 array of waveguides may be produced. With improved hole-burning material 16, increasing $\Delta\nu_I$ to 100 GHz still maintains high capacity [100GHz/1MHz (effective spectral resolution) = 10^5 bits] while facilitating shorter latencies (1 μs). In one embodiment, 10^6 bits per

spot may be supported at the latency specification of 10 μs. Also, with improved patterning techniques and alternate hosts materials, a 512X512 array of waveguides may be formed.

2. The laser source may be a frequency stabilized dye laser with tunability achieved via electro-optic means. The tunable dye laser may offer a 100 kHz stability and 10 GHz tunability. For compactness, a semiconductor laser with 100 GHz tuning in 10 μs together with < 100 kHz of tuning repeatability along with short-term frequency stability < 100 kHz may be used.

3. A bulk EO modulator may be used to achieve the 100 MHz data modulation. For a more compact design, a waveguide-based EO modulator may be utilized.

4. A 2D COTS acousto-optic router may be used to address a range of arrays of data storage locations or spots, from 64X64 to 256X256. For a compact and integrated system, a MEMS-based beam router may be used, which may eliminate the path between the router and the storage material (in the waveguide form).

5. To achieve the desired latency and data rate, the high speed addressing electronics and interface components may be fabricated in either high speed ASIC (Application Specific Integrated Circuit) or FPGA (Field Programmable Gate Array) technology.

In one embodiment, with 10^5 bits of per-spot capacity and a 64X64 array of data storage locations, the data storage capacity is 0.5 Gbits ($64X64X10^5$ = 0.5Gbits), data access latency is 10 μs latency, the sustained data transfer rate is 100 Mbps, and the read/write power is less than 1W (accounting for the numerous imperfect surfaces and sources of insertion loss in this un-optimized embodiment). In another embodiment, a 320X320 spatial array of storage locations produces a 12.5 Gbit capacity.

A computer simulation was developed to model the system 10 and estimate its performance in terms of SNR and bit-error rate. Matlab m-files were written to perform operations in the spectral domain, and Simulink program was used for time-domain simulations. In this simulation, a laser model generates time-domain data that represents the electric field generated by the laser. Parameters can be adjusted to control the phase and amplitude fluctuations in the signal. Simulation of an acousto-optic modulator and the SHB (spectral hole burning) medium are carried out in the spectral domain after taking the Fourier transform of the laser signal. Parameters for the characteristics of the acousto-optic modulator, the recorded hole depth, hole width, number of spectral channels, channel spacing, and absorption can be adjusted. The output from the SHB medium is calculated by taking the product of the modulated laser spectrum with the transmission spectrum of the medium. Various encoding techniques can be used to determine the data pattern recorded in the medium. The heterodyne receiver and RF filters are modeled in the time domain. Parameters for receiver noise, detector sensitivity, and various filter characteristics can be modified. The results indicated that spectral hole depths as low as 0.1 can provide enough contrast for good performance using appropriate coding schemes. As a result, a reduced laser power is required for writing the holes.

Fig. 5 shows graphs of experimental results obtained through measurements of a three-channel write-read process using a hole-burning material (Eu:YSO crystal) according to one embodiment of the present invention. The experimental results shown in Fig. 5 corroborate the simulated results for the computer model discussed in the previous paragraph. In Fig. 5, graph (a) shows the spectrum of a pulse used to write a single channel at 420 MHz (relative to the laser frequency which is tuned to the absorption peak of the hole-burning medium). To read the data, a pulse consisting of three frequencies, as shown in graph (b) in Fig. 5, were applied to the medium, and the output spectrum shown in graph (c) was obtained. The increased power detected at 420 MHz is a result of the recorded data. The experiment was repeated with the write pulse located at 400 MHz, and the resulting output is shown in graph (d) in Fig. 5.

Based on the simulation model and on subsequent analytical investigations, several realizations about the impact of coding, equalization, and error correction on optimal memory performance were achieved. These analyses accounted for material parameters that describe the interaction of light with spectral hole burning materials. These realizations are abstracted here.

1. Sparse and greyscale encoding - Sparsity may not be an efficient way to achieve increased data rate in a write-power-limited environment. Instead, greyscale encoding was found to offer benefits to both data rate and capacity in cases for which shallow holes can be reliably used.

2. Error correction – ECC (Error Correction Coding) was found to be an efficient way to reduce the minimum acceptable hole depth and thus increase write-parallelism. This technique will improve data rate in write-power-limited environments.

3. Differential encoding - The slowly varying nature of several SHB (spectral hole burning) distortion and noise sources makes differential coding a simple yet powerful technique for

improving data fidelity in the spectral storage system 10 (Fig. 1). Through simulation, differentially encoded data may be stored at 100 kHz hole spacing at higher fidelity than uncoded data can be stored at 200 kHz spacing.

4. Spectral equalization - The primary limiting factor for high-density storage is the spectral crosstalk among neighboring RF channels. Initial analysis of this crosstalk has shown that the channel in the spectral storage system 10 is a non-linear (i.e., exponential and multiplicative) ISI (inter-symbol interference) channel and conventional crosstalk mitigation techniques may not be applicable. Using a Taylor series representation of this nonlinear channel revealed a first-order equalizer and initial tests of its efficacy have been performed.

5. Regarding an SNR (Signal-to-Noise Ratio) Anomaly at 150 kHz channel spacing: Simulation results suggested that the SNRs for hole spacings of 100 kHz and 200 kHz were inferior to that for 150 kHz spacing. Analysis explains this phenomena in terms of the readout signal baseline. Briefly, the storage of all zeros will result in an output spectrum that varies due to the superposition of individual readout channel spectra. This variation causes a broadening of the zero peak in a BER (bit error rate) histogram. At 150 kHz hole spacing these individual readout channel spectra begin to merge, smoothing the all-zero baseline. Of course, 100 kHz spacing also results in a smooth baseline, however, crosstalk has also risen to dominate the baseline effect when that narrow channel spacing is employed.

6. Anti-Hole effect on data recall fidelity: Early simulations incorporated only a few data holes and were therefore optimistic with respect to predicted readout SNR. Later studies increased the number of neighboring recorded holes and incurred the degrading effects of numerous noise sources. This study slowly increased the number of holes (at constant spacing) to reveal the impact of each noise source individually. A particularly dramatic effect arises when the first anti-hole begins to affect the recorded data. SNRs drop from the range of 250 down to 30 as the first anti-hole spectral location overlaps a data spectral location. This result is for 200 kHz spacing and is independent of hole depth. SNR=30 is still achieved, which suggests that complicated methods to deal with this source of crosstalk are not yet required.

7. Rise-Time Study: The spectral width of a data feature is related to the rise time of the associated recording/readout pulse. Both the baseline effect (described in item 5 above) and

crosstalk are impacted by the risetime. For 200 kHz spacing of 50 holes (no anti-hole degradation), the SNR can vary from 200 for slow rise time (smooth baseline) to 40 for fast rise time (bumpy baseline). The optimum LO (light output) delay is related to the readout pulse risetime.

8. Baseline Correction: There are variations in the readout signal levels for both 1's and 0's as a function of spectral location. Initially, a "local" encoding method (differential encoding) was utilized to mitigate these slowly varying distortions. The coding overhead however, was a factor of two. A method of reducing this cost was discovered. Because the baseline variations represent a fixed-noise source, it is possible to calibrate the system to remove such variations. This baseline correction was incorporated in the simulator and run a large number of trials. Using 150 kHz hole spacing and 600 bit data revealed that baseline correction provides an SNR of nearly 6 without any coding whatsoever. Without baseline correction the SNR in this case was near 1.

9. Equalization (EQ): This is a method of characterizing the crosstalk behavior of the storage channel and inverting it to retrieve higher-fidelity data. The theory of equalization for SHB memories was developed. The importance of equalization for high density spectral storage system 10 (Fig. 1) is demonstrated by comparing EQ with Differential Coding and Baseline Correction. The most important result is that 1000 holes can be placed at 100 kHz spacing and using baseline correction, equalization, and differential encoding the SNR becomes an impressive 9.8. Minimal error correction is required to extract a user BER = 10^{-15} from this performance.

10. Partial Response Signaling: relaxing the coding overhead of the differential method. Instead of encoding a single bit as a pair, the N-bit spectral word can be considered as a set of M blocks. Each block utilizes one known bit (a fiducial) and is encoded as a differential sequence based on differences between neighboring bits. The overhead is reduced but the possibility of error propagation makes the block size a critical parameter that should be designed in conjunction with the "outer" error correction code. Detailed experimental noise measurements may be required to complete this design exercise.

Analysis has been performed to determine the optical power needed to perform write and read operations under the requirement of pre-determined SNR. This analysis indicates that

Eu:YSO optimally supports storage in which the read-out optical power is commensurate with the write power, given limits on the available optical illumination and on the access latency and I/O bandwidth. This may lead to a requirement for re-write after read to ensure continued date fidelity. The target memory (using a hole-burning material) specifications include 80 Gbits capacity in a module of 1000 x 1000 = 10^6 addressable locations in an area of about 1 cm^2. This requires 80,000 spectral bins per spot. The latency requirement to first retrieved bit is 10 microseconds. Burst I/O of 80 Gbit/sec is required, with no more than 60 % time allocated to memory management activities. The optical power required to meet these performance specifications is less than 1 watt for the Eu:YSO system. Other materials may improve the power requirement. This analysis has also led to a list of preferable attributes for emerging inhomogeneously broadened spectroscopic materials that can support spectral hole burning memory applications.

The foregoing describes a system and method to spectrally store data in a spectrally addressable hole-burning material, such as an Eu (Europium)-doped YSO (Yttrium Silicate) crystal. The digital data to be spectrally stored is first converted into an RF (radio frequency) form by modulating the data using multiple RF frequencies, with each RF frequency carrying one of the data bits. The RF-encoded data is then optically modulated by an electro-optic modulator using one or more laser frequencies as carriers. The optically modulated output is sent to a beam router that projects the output onto a predetermined location or spot on the storage material. The hole-burning material is shaped as an array of waveguides to combat light diffraction and maintain high spatial storage density. The stored data is read using a high speed detector along with a bank of RF filters. The use of laser tuning together with parallel RF modulation allows access to the full inhomogeneous spectrum of the hole-burning material storing the data.

Because the addressing of the data storage locations is massless (i.e., does not involve any moving parts), the spectral data storage system according to the present invention can be suitably used as a computer memory that has storage capacity and data rate values competitive with commercial magnetic hard drives while the data access latency is thousand-fold less than that for commercial hard drives. Additionally, multiple spectral storage systems according to the present invention may be combined in a RAID (Redundant Array of Independent Disks)-like implementation for increased storage capacity and fault tolerance, without sacrificing data access latency or in a rotating disk implementation in which capacities exceeding 100 TB are possible for applications in which the rotational latency is acceptable. A memory unit employing the data storage system of the present invention may be useful to provide storage for memory intensive applications such as scientific computing, database management, audio/video processing and storage, and network services.

While the invention has been described in detail and with reference to specific embodiments thereof, it will be apparent to one skilled in the art that various changes and modifications can be made therein without departing from the spirit and scope thereof. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

CLAIMS

1. A system for spectrally storing data in a hole-burning material, wherein said data includes a plurality of data bits, and wherein an optical spectrum of said hole-burning material has an inhomogeneous linewidth constituted of a plurality of homogeneous linewidths, said system comprising:

an electro-optic (EO) modulator configured to receive an RF (Radio Frequency)-encoded data signal as a first input and a laser signal as a second input, wherein said RF-encoded data signal contains said plurality of data bits in an RF form, and wherein said EO modulator optically modulates said RF-encoded data signal using said laser signal as a carrier signal, thereby generating an optically modulated output; and

a beam router optically coupled to said EO modulator to receive said optically modulated output therefrom and thereafter to project said optically modulated output onto said hole-burning material to spectrally record said data therein.

2. The system of claim 1, further comprising a laser device coupled to said EO modulator to supply said laser signal thereto.

3. The system of claim 2, wherein said laser device is a tunable laser device that, upon tuning, outputs a plurality of laser frequencies, and wherein said laser signal contains at least one of said plurality of laser frequencies.

4. The system of claim 3, wherein at least one of said plurality of laser frequencies lies within said inhomogeneous linewidth of said hole-burning material.

5. The system of claim 1, wherein said plurality of data bits is represented as a corresponding plurality of optical frequency components in said optically modulated output, and wherein each of said plurality of optical frequency components spectrally stores a corresponding one of said plurality of data bits at a respective one of said plurality of homogeneous linewidths.

6. The system of claim 5, wherein each of said plurality of optical frequency components bleaches a spectral absorption of said respective one of said plurality of homogeneous linewidths to spectrally store corresponding one of said plurality of data bits.

7. The system of claim 1, wherein said beam router is a microelectromechanical systems (MEMS)-based device.

8. The system of claim 1, wherein said beam router includes a two-dimensional array of a plurality of micro-mirrors.

9. The system of claim 8, wherein each of said plurality of micro-mirrors is electrically addressable individually to project said optically modulated output onto a corresponding portion of said hole-burning material.

10. The system of claim 1, wherein said hole-burning material includes a pattern of waveguides, wherein each of said waveguides is configured to function as a storage location to spectrally store therein said optically modulated output projected from said beam router.

11. The system of claim 1, further comprising:
an opto-electric transducer configured to sense an illuminated output from said hole-burning material and thereafter convert said illuminated output into an equivalent electrical signal, wherein said illuminated output is generated when said hole-burning material is illuminated with said optically modulated output that is fully modulated.

12. The system of claim 11, further comprising:
a detector unit configured to receive said electrical signal from said transducer and thereafter to demodulate said electrical signal to generate a plurality of RF baseband signals therefrom, wherein each of said plurality of RF baseband signals contains one of said plurality of data bits in said RF form.

13. The system of claim 12, further comprising:
a plurality of RF filters coupled to said detector unit, wherein each of said plurality of RF filters receives a corresponding one of said plurality of RF baseband signals as input and outputs a respective one of said plurality of data bits in a digital form.

14. A data storage device comprising:
a hole-burning material having an optical spectrum that has an inhomogeneous linewidth constituted of a plurality of homogeneous linewidths;
an electro-optic (EO) modulator configured to receive an RF (Radio Frequency)-encoded data signal as a first input and a laser signal as a second input, wherein said RF-encoded data signal contains a plurality of data bits in an RF form, and wherein said EO modulator optically modulates said RF-encoded data signal using said laser signal as a carrier signal, thereby generating an optically modulated output; and
a beam router optically coupled to said EO modulator to receive said optically modulated output therefrom and thereafter to project said optically modulated output onto said hole-burning material to spectrally record said data therein, wherein said beam router includes a two-dimensional array of a plurality of MEMS (microelectromechanical systems) micro-mirrors, and wherein each of said plurality of micro-mirrors is electrically addressable individually to project said optically modulated output onto a corresponding portion of said hole-burning material.

15. The device of claim 14, wherein said hole-burning material is an Eu-doped-YSO crystal.

16. The device of claim 15, wherein said hole-burning material comprises a pattern of waveguides, wherein each of said waveguides is configured to function as a storage location to spectrally store therein said optically modulated output projected from said beam router.

17. The device of claim 16, wherein each waveguide in said pattern of waveguides is cylindrical in shape.

18. The device of claim 15, further comprising:

an opto-electric transducer configured to detect an illuminated output from said hole-burning material and thereafter convert said illuminated output into an equivalent electrical signal, wherein said illuminated output is generated when said hole-burning material is illuminated with said optically modulated output that is fully modulated;

a detector unit configured to receive said electrical signal from said transducer and thereafter to demodulate said electrical signal to generate a plurality of RF baseband signals therefrom, wherein each of said plurality of RF baseband signals contains one of said plurality of data bits in said RF form; and

a plurality of RF filters coupled to said detector unit, wherein each of said plurality of RF filters receives a corresponding one of said plurality of RF baseband signals as input and outputs a respective one of said plurality of data bits in a digital form.

19. A method of spectrally storing data in a hole-burning material comprising:

receiving an RF (Radio Frequency)-encoded data signal containing said data in an RF form;

optically modulating said RF-encoded data signal using a laser beam as a carrier, thereby generating an optically modulated output; and

routing said optically modulated output to a predetermined location on said hole-burning material, thereby spectrally storing said data at said predetermined location.

20. The method of claim 19, wherein routing said optically modulated output includes projecting said optically modulated output onto a plane containing said hole-burning material.

21. The method of claim 19, wherein receiving said RF-encoded data signal includes receiving a plurality of RF signals with each signal containing a corresponding one of a plurality of data bits in said RF form, wherein said plurality of data bits constitutes said data.

22. The method of claim 19, further comprising providing a guiding channel to said optically modulated output routed to said predetermined location on said hole-burning material.

23. A method of reading data spectrally stored at a location on a hole-burning material, said method comprising:
optically modulating an RF (Radio Frequency)-encoded data signal using a laser beam as a carrier, wherein said RF-encoded data signal contains a plurality of data bits in an RF form and wherein each of said plurality of data bits has an identical value, thereby generating a fully modulated laser beam;
illuminating said location with said fully modulated laser beam;
detecting an optical output emanating from said illuminated location; and
retrieving said data from said detected optical output.

24. The method of claim 23, wherein illuminating said location includes:
optically routing said fully modulated laser beam to said location on said hole-burning material; and
guiding said optically routed fully modulated laser beam towards said location on said hole-burning material to illuminate said location with said guided fully modulated laser beam.

25. The method of claim 23, wherein detecting said optical output includes:
converting said optical output into an electrical signal; and
demodulating said electrical signal to generate a demodulated RF signal containing said data in said RF form.

26. The method of claim 25, wherein retrieving said data includes filtering said demodulated RF signal to retrieve said data therefrom.

27. A memory unit comprising:
a plurality of waveguides, wherein each of said plurality of waveguides is formed of a hole-burning material to spectrally store data therein; and
a support medium having a low optical refractive index, wherein said support medium physically separates each waveguide in said plurality of waveguides and provides a supporting layer for said plurality of waveguides.

28. The memory unit of claim 27, wherein at least one of said plurality of waveguides is cylindrical in form.

29. The memory unit of claim 27, wherein said support medium is Epoxy.

30. A method of forming a memory unit comprising:
forming a plurality of waveguides using a substrate of a hole-burning material;
supporting said plurality of waveguides with a support medium having a low optical refractive index; and
removing a portion of said substrate where said plurality of waveguides is absent.

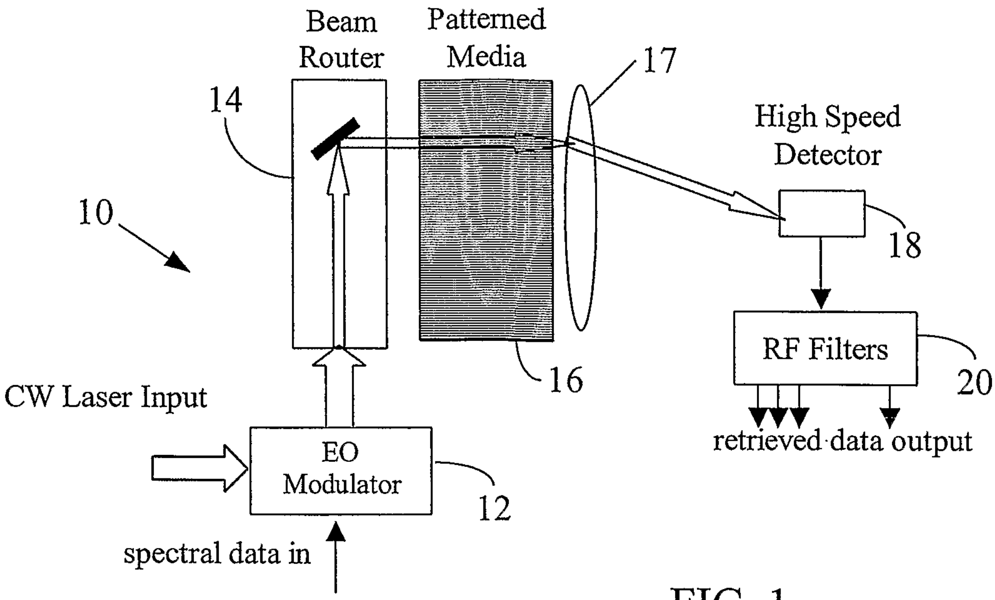
Beam
Router
Patterned
Media
17
14
High Speed
Detector
10
18
RF Filters
16
20
CW Laser Input
retrieved data output
EO
Modulator
12
spectral data in

FIG. 1

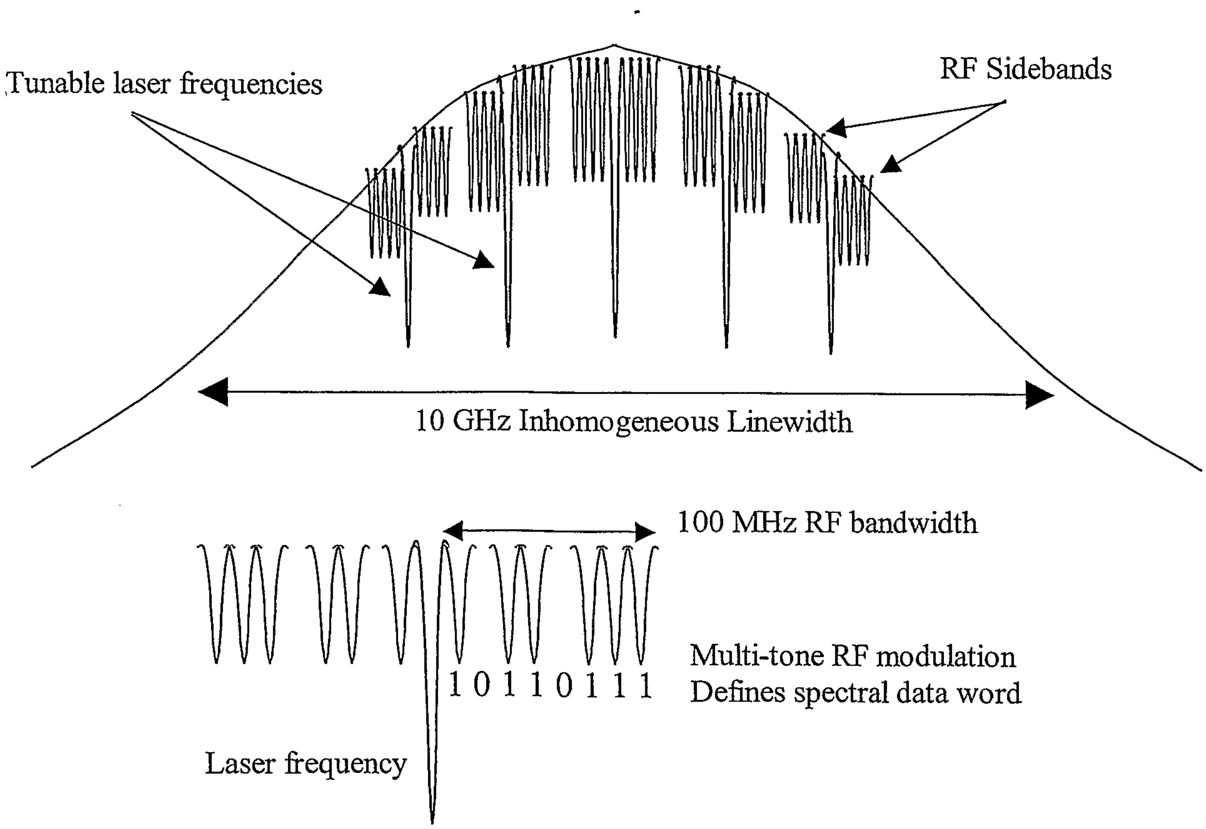
Tunable laser frequencies
RF Sidebands
10 GHz Inhomogeneous Linewidth
100 MHz RF bandwidth
Multi-tone RF modulation
Defines spectral data word
1 0 1 1 0 1 1 1
Laser frequency

FIG. 2

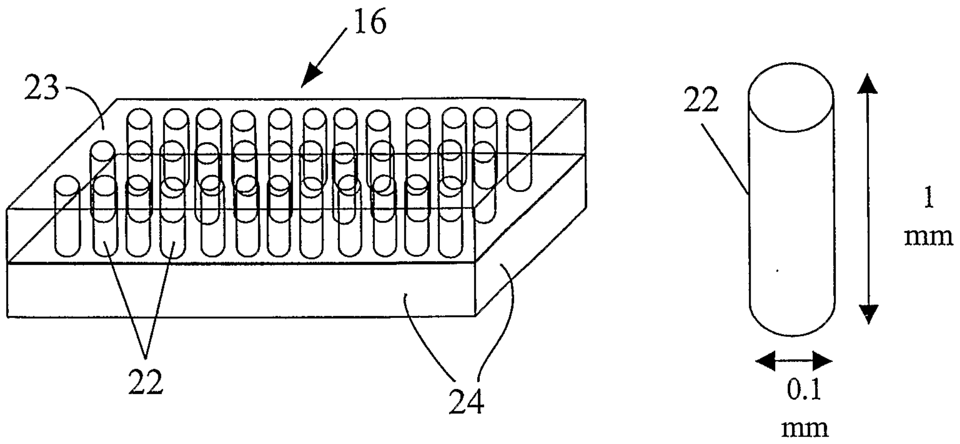
16
23
22
22
24
1
mm
0.1
mm

FIG. 3

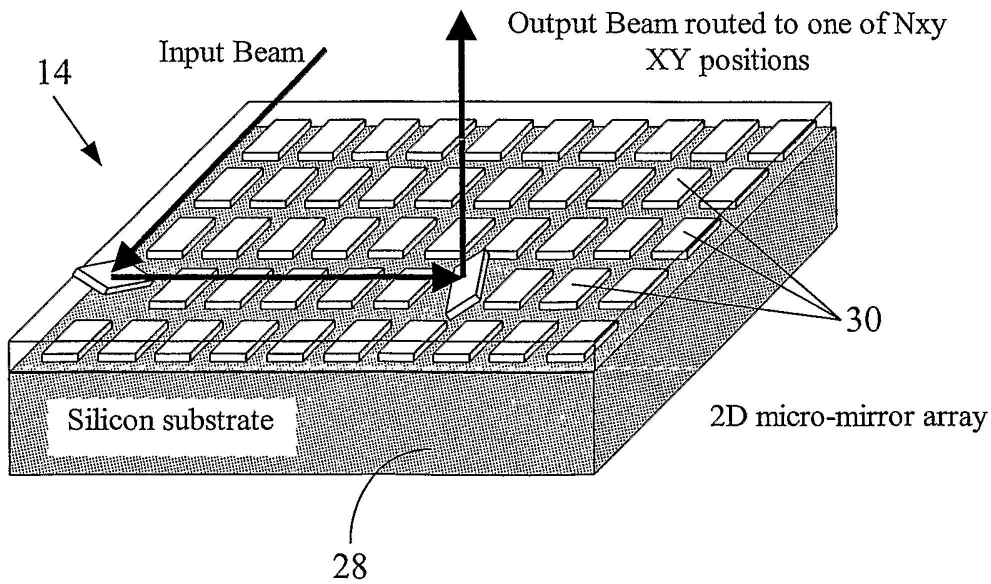
Input Beam
14
Output Beam routed to one of Nxy
XY positions
30
Silicon substrate
2D micro-mirror array
28

FIG. 4

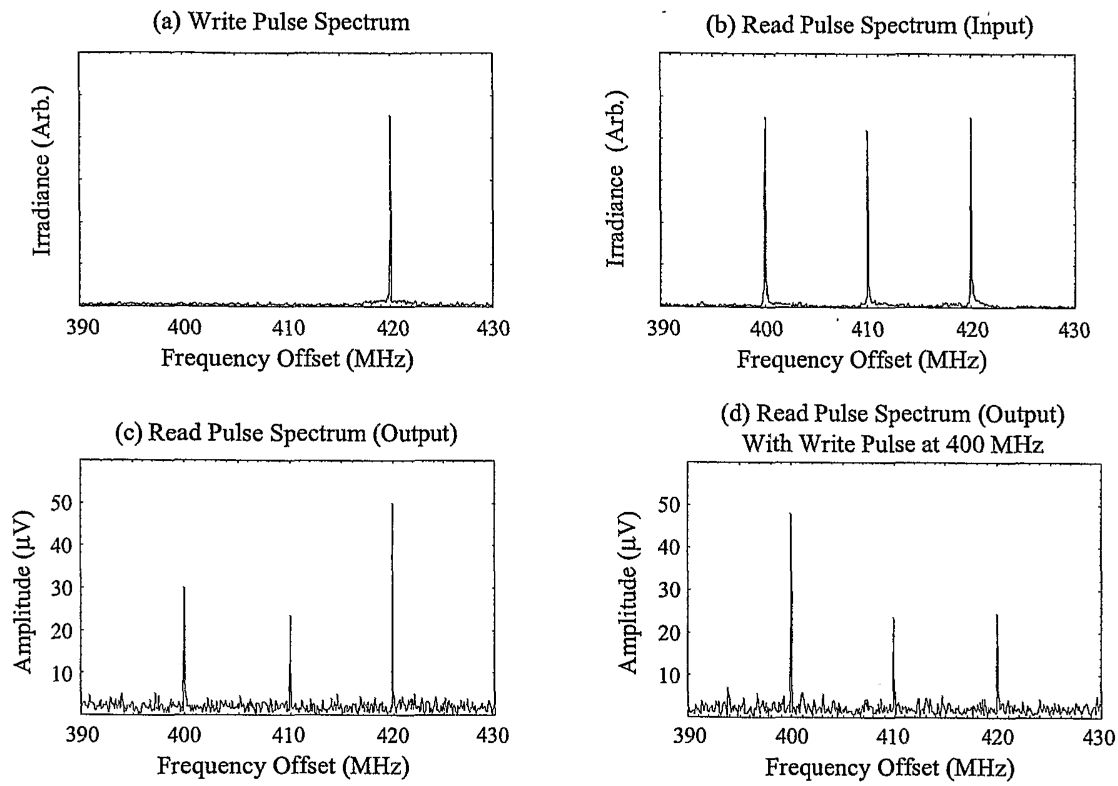
(a) Write Pulse Spectrum
Irradiance (Arb.)
390 400 410 420 430
Frequency Offset (MHz)
(b) Read Pulse Spectrum (Input)
Irradiance (Arb.)
390 400 410 420 430
Frequency Offset (MHz)
(c) Read Pulse Spectrum (Output)
Amplitude (μV)
10 20 30 40 50
390 400 410 420 430
Frequency Offset (MHz)
(d) Read Pulse Spectrum (Output)
With Write Pulse at 400 MHz
Amplitude (μV)
10 20 30 40 50
390 400 410 420 430
Frequency Offset (MHz)

FIG. 5