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Towards massively parallelized all-optical magnetic recording

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We demonstrate an approach to parallel all-optical writing of magnetic domains using spatial and temporal interference of two ultrashort light pulses. We explore how the fluence and grating periodicity of the optical transient grating influence the size and uniformity of the written bits. Using a total incident optical energy of 3.5 μJ, we demonstrate the capability of simultaneously writing 10^2 spatially separated bits, each featuring a relevant lateral width of $\sim$1 μm. We discuss viable routes to extend this technique to write individually addressable, sub-diffraction-limited magnetic domains in a wide range of materials. *Published by AIP Publishing.* https://doi.org/10.1063/1.5003713

I. INTRODUCTION

The ability to switch magnetic domains using ultrashort pulses of light holds substantial promise for future development of data storage technologies, most importantly by increasing the write speed to terahertz repetition rates while reducing or removing entirely the Joule heating and stray magnetic fields associated with present day technologies based on strong localized magnetic fields. Since its first demonstration in 2007,[1] helicity-dependent all-optical switching (HD-AOS) has launched a new field of research[2–4] devoted to making all-optical switching a viable methodology for recording information.

To date, a vast array of materials have shown some form of all-optical writing of stable magnetic domains. The simplest approach, termed helicity-independent deterministic switching,[5] relies exclusively on the ultrafast heating supplied by the optical pulse, whereby a single light pulse will switch the magnetization regardless of the initial magnetization state. At a fluence just below the threshold required for deterministic switching, magnetic circular dichroism[6] (in combination with the ultrafast heating) can instead be used to achieve HD-AOS. While deterministic switching has so far only been demonstrated in GdFeCo[5,7] and TbFeCo,[8,9] HD-AOS is exhibited by a large class of materials (rare earth-transition metals,[1,10–12] synthetic ferrimagnetic heterostructures,[12,13] and multilayered/granular ferromagnets).[14,15] Depending on the material, HD-AOS requires either a single pulse (e.g., GdFeCo)[5] or a number of repeated pulses (e.g., CoPt).[14] Finally, it was recently shown[16] that the magnetization in a transparent dielectric (cobalt-substituted yttrium-iron-garnet) can be all-optically switched using a single linearly polarized light pulse. The microscopic physics underpinning most (if not all) of these routes is still the subject of intense debate.[4,17,18]

In order to improve the capabilities and technological exploitability of all-optical switching, substantial attention has deservedly been focused on quantifying and increasing the speed of all-optical switching,[7,16,19] miniaturizing the optically (or plasmonically) addressed domains,[8,9,20–23] expanding the pool of optically manipulatable magnetic materials,[12,14,16,23] and integrating all-optical switching within electronic and spintronic architecture.[24–27] In order to parallelize the process of all-optical switching, one could (for example) pattern the recording medium. This enables spatially uniform optical pulses to write individually addressable domains at sub-diffraction-limited length scales, via the structure's non-uniform focussing properties.[28] No research so far, however, has explored the possibility of manipulating more than one magnetic domain at a time through the spatial patterning of light.

In this letter, we address the issue of parallel writing of domains, thus opening avenues to substantially increase the write speeds using the mechanism of all-optical switching. Our solution uses intensity-gratings generated via the spatial interference of two similarly linearly polarized light pulses. By exposing a suitably prepared sample to such a spatially tailored excitation, in single-shot mode, we demonstrate that one can deterministically switch the magnetization of many magnetic bits simultaneously. While still limited by the diffraction limit, we nonetheless demonstrate the writing of $\approx 10^2$ bits, with a relevant lateral dimension down to 1 μm using energies of about 35 nJ per bit. We discuss avenues to writing $> 10^6$ individually addressable bits with a single ultrashort pulse, and potentially achieving sub-diffraction-limited bit sizes using interference patterns featuring variation not only of intensity but also of polarization.

II. EXPERIMENTAL METHODOLOGY

In our experiment, ultrashort linearly polarized optical pulses were generated by a Spectra-Physics Spitfire regenerative amplifier, with a central wavelength of 800 nm, pulse

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width of 35 fs, and triggered for single pulse operation. The critical optical element we employ is the binary phase mask array, consisting of a series of square-profile etched glass phase gratings optimized for ± 1 diffraction efficiency at 800 nm. The phase mask is imaged with demagnification onto the sample surface using only these ± 1 orders, resulting in a sinusoidal interference pattern enveloped by a radially symmetric Gaussian distribution.[29] Lateral translation of the phase mask array provides for the writing of different grating periodicities onto the sample surface while maintaining a constant beam diameter of about 200 μm (at 1:1 demagnification of the writing pulse). All reported fluence values here are given as total combined pulse energy/area and thus do not account for the peak and troughs of the interference pattern. When operated for time-resolved studies, this excitation scheme is termed transient grating spectroscopy and intensity gratings are often used for measuring elastic dynamics in the visible[30,31] and extreme ultraviolet[32,33] spectral regimes, phase change phenomena via core level spectroscopy,[34] and dynamics of spins[35] and electrons in semi-[36] and superconductors.[37] Recently, the technique has also been extended to elucidate magnetoelastic effects in ferromagnetic films, a review of which can be found in Ref. 38.

A small portion of the linearly polarized laser beam is used for full field imaging of the resultant static out-of-plane magnetization profile across the sample surface via the magneto-optical Faraday effect.[39] After transmitting through the sample at normal incidence, the imaging beam is collected by an objective lens (Mitsutoyo, G Plan APO $\times 20$, NA $= 0.28$), passed through an analyzer, and detected by a CCD camera (QImaging, Retiga R3). Coupled to the CCD camera is a variable magnifier ($\times 0.58$– $\times 7.0$), affording us a lateral spatial resolution ranging between 2 μm and 400 nm. The sample is saturated into a single domain prior to the write beam pulses being applied, and images are acquired after the domains are written but in the absence of the write beams. All measurements presented here are performed in the static regime.

Experiments are performed on the ferrimagnetic amorphous alloy GdFeCo, which was grown by magnetron sputtering, and features perpendicular magnetic anisotropy and transparency in the visible range. The multilayer structure for this sample is glass(0.5 mm)/SiN(5 nm)/Pt(2 nm)/$Gd_{22}Fe_{68.25}Co_{9.75}$(20 nm)/SiN(5 nm). The dynamics of magnetization switching in this film (and films like it) has been comprehensively studied.[1,5,7,40–42]

III. RESULTS

Figure 1 shows an example of multiple magnetic bits written in parallel using a single pulse intensity grating for a nominal grating period of 2.5 μm and thus a switched domain size of (1.3 ± 0.2) μm. Apart from small defects originating from the instability of micron-sized magnetic domains in the magnetically soft GdFeCo,[9] the intensity grating excitation writes long, vertically aligned magnetic domains (dark blue) in the otherwise oppositely saturated (light yellow) domain region. The written bits fill the entire aperture of the write beam and exceed the field of view of the magnifier employed in the imaging system. A zoom in of various regions of the written pattern demonstrate the fidelity of the written pattern and the constant width of the written domain. The total incident pulse energy to write this pattern, consisting of about 100 stripes (with 50% duty cycle), is 3.5 μJ and thus each stripe requires 35 nJ of optically delivered energy. This cost, neglecting the substantial energy costs of generating ultrashort optical pulses, is comparable to that paid in existing hard drives (10–100 nJ).[43]

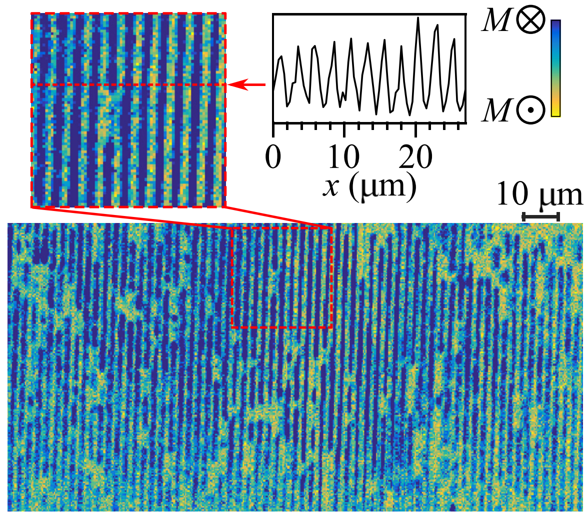

FIG. 1. A raw magneto-optical image of a section of the magnetic domains written by a single pulse intensity-grating of periodicity 2.5 μm. Also shown is a zoomed (27×27) μm^2 section of the magnetization distribution and an accompanying cross section. The width of the written domains is (1.3 ± 0.2) μm.

We study the effect of excitation fluence on the domain width. We measure the width of the largest bit(s) at the centre of the grating as shown in Fig. 2 for two representative gratings periods, 17 μm and 8.5 μm. The size of the domain reduces monotonically as the excitation fluence is reduced, and we identify three regimes of variation. At high fluence, the domain width saturates close in size to that of the full grating period, indicating that nearly the entire sample region switches (see top inset in Fig. 2). As the fluence is decreased from this regime, there is a sharp reduction in the domain width, and finally below a certain fluence value, the domains again become constant in size. This lowest saturated value is close to the expected imaging resolution for this particular set of measurements (2 μm) and suggests the possibility that our ultimate bit width is unresolved. The insets in Fig. 2 show several background-corrected written bit patterns for a range of fluences, delineating these effects. Again, at high fluences, we witness wide switched domains displaying demagnetization at their center. Farther in the wings of the beam aperture, the intensity reduces such that uniform switching is evident over a smaller lateral region. In totality, Fig. 2 provides a roadmap for reducing written domain sizes, to a limit ultimately dictated only by the material under study. Namely, by optically engineering a large aperture, flat top beam one could write thousands of domains simultaneously, while the domain size itself is determined only by the portion of the interference crests that meet the thresholding condition.

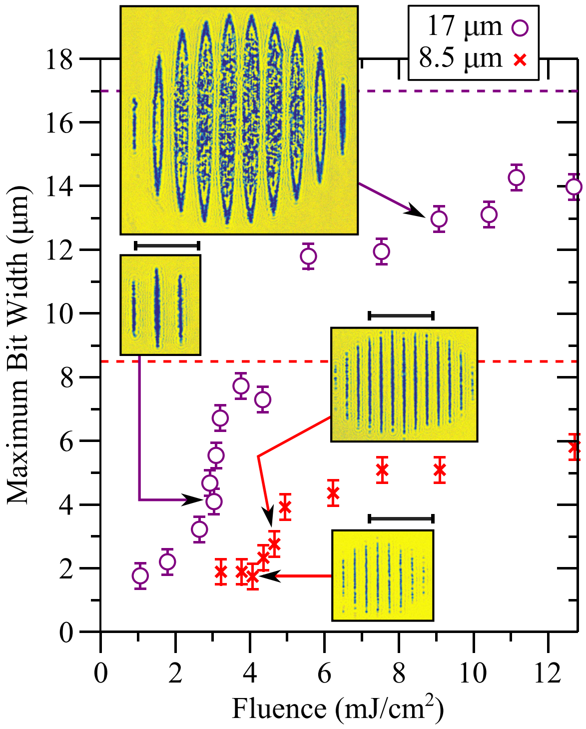

FIG. 2. The maximum bit width written by the single-shot intensity-grating as a function of the fluence, for different periodicities as indicated. Also shown are exemplary images of the entire grating written at different fluences, equally graded in color such that dark blue and light yellow indicate that the magnetization has been switched and not switched, respectively. The scale bar, common to all images, corresponds to 50 μm.

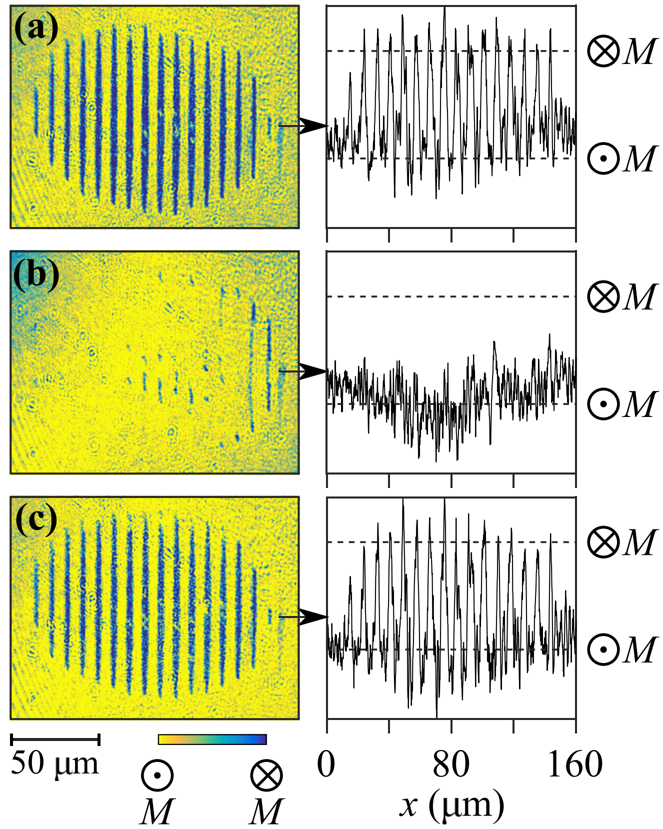

FIG. 3. Background-corrected magneto-optical images of the magnetization after exposure to $n=$ (a) 1, (b) 2, and (c) 3 intensity grating excitations, and accompanying cross sections. The intensity grating had a periodicity of 8.5 μm and fluence 4.9 mJ/cm^2.

Finally, the deterministic switching in these alloys[5,7] allows one to sequentially overwrite magnetic domains onto the same portion of the sample. In Fig. 3, we show a sequence of intensity grating excitations, demonstrating that the domains reverse for each optical exposure, provided that the intensity grating retains its intensity and spatial positioning. It is important to note that this toggling behaviour can only be achieved in the absence of demagnetization (see, e.g., the image in the top inset of Fig. 2, where this effect is apparent). If the optical fluence and maximum bit width are both large enough to permit demagnetization to occur, the demagnetized region will not reverse with each shot.

IV. DISCUSSION

We provide our vision for future developments in this field, targeting the writing of 10^6 bits simultaneously using a single laser pulse. We take as our starting point a material capable of supporting nanometer sized domains written through deterministic switching (e.g., TbFeCo).[9] At the position of the sample, the local intensity falling on any given point is determined by the interference of two wavefronts originating, respectively, from each of the two beams in the interferometer. Thus, modulating the relative arrival time or polarization of either of the two interfering pulses will modulate the local intensity or polarization of light falling on the sample.[44] To affect this modulation, one could envisage a scenario where an active optical element (i.e., a two-dimensional spatial light modulator, 2D-SLM[45]) programmably varies the phase delay or polarization of one (or both) of the interfering pulses. Thus, the one-dimensional grating pattern we now employ could be augmented to become a two-dimensional, individually addressable intensity pattern,[46–48] through destructively or constructively interfering the two optical pulses on a pixel-by-pixel basis across the sample surface. A commercially available 2D-SLM with ∼100% fill factor and >8 × 10^6 bits (Thorlabs Exulus-4K1 or Holoeye GAEA-2) operates at 30 Hz. If optimally utilized, this configuration achieves write speeds of >0.2 Gb/s. By increasing the repetition rate and pixel count of the employed 2D-SLM, this writing speed can be boosted further. Current hard disk drive technology, in comparison, features write speeds up to ∼0.1 Gb/s (boosted further to ∼1.2 Gb/s by the parallel use of multiple write heads), and solid-state drives boost writing speeds up to ∼17 Gb/s.

In order to achieve comparable read-out speeds, one could use magnetic tunneling junctions (MTJs);[49] recently, it has been demonstrated[27] that GdFeCo can serve as an optically controllable free layer within a MTJ, allowing tunneling magnetoresistance to be used for read-out. This approach, however, requires complex patterning of the recording medium and has already been successfully implemented all-electrically in magnetic random access memory. In order to retain a simpler single read-/write-head approach, one could rather use an all-optical readout (already demonstrated in the MiniDisc technology) or near-field magneto-optics.[50]

The domain sizes achievable are only determined by the material in question and the stability of the optical source.

Considering a large aperture, flat top optical wavefront (unlike our tight focusing geometry), the written domain sizes are dictated only by the regions of constructive interference that meet the threshold condition for switching a domain.[51,52] In Ref. 53, for example, the threshold character of AOS was exploited to write a magnetic domain of width 300 nm, using light of wavelength 800 nm. Combination with pre-patterned media[54] could result in further bit-size reduction towards the length-scales of 30 nm found in modern hard-disk drives (and we emphasize the fact that AOS has already been experimentally shown to be capable of deterministically writing domains of diameter 53 nm).[9] Furthermore, there is the possibility of multiplexing by spatially rastering the sample (using, e.g., a Thorlabs MLS203 motorized stage) during the writing process. Rastering speeds are modest, being comparable to that at which the light modulation is occurring. This strategy does not increase the writing speed, but rather increases the density of the written material.

In terms of energy costs per bit, assuming the aforementioned lossless 2D-SLM, the 10^2 bits we demonstrate here (Fig. 1) become 10^4 (assuming a beam of fixed diameter hitting $N * N$ pixels of the 2D-SLM) while the total energy falling on the sample remains unchanged, reducing the energy/bit ratio to 350 pJ for 50% duty cycle bits (lower for smaller aspect ratios). Energy costs could continue to reduce depending on the material in question.

Finally, we note that the optical interference phenomenon shown here belongs to a broad (and complex) family of interference patterns described in Ref. 44. For example, by rotating the linear polarization of one of the interfering pulses (and compensating the phase delay of the other by means of a pair of glass wedges) so as the two pulses are orthogonally polarized, one generates a polarization grating, characterized by uniform intensity profile and spatially alternating helicity.[55] This interference pattern could be used to achieve HD-AOS in a much larger range of materials (e.g., synthetic ferrimagnets[12,13] and granular ferromagnets[14,15]). The fluence and helicity thresholds could then be exploited in tandem to potentially achieve all-optical switching at domain sizes smaller than those manipulated using intensity gratings. Alternatively, interference between left- and right-circularly polarized light pulses yields an intensity pattern that has a uniform intensity profile but spatially oscillating linear polarization (from vertical to horizontal orientation).[56] This could be exploited to achieve all-optical switching in magnetic dielectrics, which depends on the orientation of the linear optical polarization state.[16] It stands to reason that any and all such interference phenomena should be investigated in order to improve efficiencies, increase writing speeds, and provide for full control over magnetic properties in a variety of materials.

V. CONCLUSION

In summary, we have optically written multiple magnetic domains simultaneously using optical interference. Using intensity interference patterns, we demonstrated the writing of 10^2, $\sim 1\,\mu$m domains with a single laser pulse where each domain required 35 nJ of energy to switch. We presented our vision for further parallelization utilizing all-optical switching, wherein active control of the interfering wavefronts could result in writing $\sim 10^6$ individually addressable domains simultaneously at rates of ~ 0.2 Gb/s. Finally, we note the breadth of optical interference phenomena that could be achieved by varying the intensity, polarization, and phase delay of the individual interfering beams.

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