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Thermal aspects of magneto-optical recording

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We discuss the influence of thermal response on the magneto-optic readout performance of optically similar but thermally different quadrilayer media, using newly developed computational techniques for examining laser-induced heat flow in moving multilayer media. We first emphasize the importance of time scale for differentiating the write and read processes. We then show that the optimum design is a function of the medium velocity and available laser power for writing and is not normally one that provides maximum signal-to-noise ratio in the limit that laser heating during readout can be ignored. Finally, we describe a systematic approach to the selection of the best quadrilayer design for a given set of system conditions.

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I. INTRODUCTION

In earlier work, we considered how a differential detection system and magneto-optical medium could best be configured for readout by the polar Kerr effect.[1,2] It was found that the generic optimum structure of the medium itself was closely related to the trilayer metal-dielectric structures that have been long used in optics when absorption in a thin metal layer is required.[3,4] In particular, Bell and Spong[5] have pointed out that this structure is most useful for ablative optical recording because the maximum light absorption occurring in the thin metal film results in a maximum writing sensitivity. In our case, we made use of the structure somewhat differently. Its characteristics were no longer designed for maximum light absorption, but rather were optimized along with the detection system parameters to give a maximum signal-to-noise ratio for magneto-optical readout by the polar Kerr effect. Typically the structure of the medium is then quite different from that for maximum light absorption. Indeed the signal-to-noise ratio for the latter is usually very small with a differential detection system.

While heating of the medium during readout was recognized in our earlier work[2] as an important parameter in the selection of an optimized system, it was included only inasmuch as media requiring different write powers can obviously withstand different read powers. This feature of the problem is closely related to earlier work done on the thermal aspects of ablative recording,[6,7] but now it is no longer important to maximize the writing sensitivity by preventing heat flow from the light absorbing layers, but rather to encourage it, subject to thermomagnetic writing remaining possible. This then allows a maximum of power to be used in readout. The approach we took earlier therefore represents a reasonable beginning to the solution of the complete readout problem, but it omits an important quantitative difference between the write and read processes, namely time scale. The consequences of this are demonstrated in Fig. 1 by calculations that simulate the thermal write process for a stationary quadrilayer medium. (The details of the layer structure are given in the figure caption.) In this example, the medium is irradiated for 50 ns by a 5-mW laser pulse focussed in a Gaussian beam to an e^{-1} radius of 500 nm. The point to note is that, independent of the temperature rise needed for writing the magnetic film, the writing process itself is completed prior to the establishment of thermal equilibrium. In contrast, readout is done in steady state, and our example therefore implies that readout must be carried out with even less power than might straightfowardly be deduced from the write power of the medium alone. The remainder of this paper will be concerned therefore with the problem of the selection of magneto-optical interference structures that provide best overall system operation when these differences between reading and writing are properly included. Moreover, the effects of relative motion of the laser beam and magneto-optic medium on the selection process are fully explored.

The paper is organized as follows. The computational procedures are outlined in Sec. II and then used in Sec. III to discuss the influence of thermal response on the read-write performance of optically similar quadrilayer media. Finally, the conclusions of the work are presented in Sec. IV.

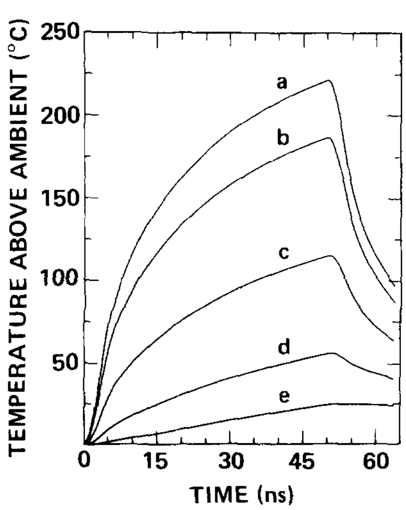

FIG. 1. Increase of temperature vs time at radii of (a) 0, (b) 250, (c) 500, (d) 750, and (e) 1000 nm that occurs in the magnetic film of a quadrilayer medium. The quadrilayer consists of a 50-nm-thick aluminum layer, and 80-nm-thick quartz intermediate layer, a 15-nm-thick magnetic metal, and a 120-nm-thick quartz overlayer. The thermal and optical parameters are given in Table II.

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II. BRIEF OUTLINE OF THE COMPUTATIONAL PROCEDURES

We describe the technique fully elsewhere,[8] but the basis of the method is readily understood. We assume that the medium is moving with constant linear speed V and then approximate this motion by a step-like progression in which the medium jumps a distance $V\Delta t$ at the end of each time interval Δt. During each Δt, however, the medium is stationary and the static technique, used earlier[9] for the calculation of temperature distributions generated in multilayer media by the incidence of a Gaussian laser beam, is applicable to the problem. Moreover, for the specific case of temperature independent optical and thermal parameters, the absorption and diffusion equations become linear, and the moving medium problem may be solved by the superposition of these static solutions at progressive time intervals.

In the present case, we are mostly interested in the laser power required to heat the magnetic medium to a certain temperature for different values of V in two situations: when the laser pulse length is r_0/V, with r_0 being the e^{-1} radius of the Gaussian laser spot, and when the pulse is long enough for thermal equilibrium to be established. The two cases, therefore, relate to that of writing at fixed resolution (for a given magnetic field) and reading under fixed illumination, respectively. The results obtained will provide the required information for the complete optimization of the medium in a magneto-optical recording system. We also show the isotherms obtained during the read process for various media at the typical medium velocity of $V = 20$ m/S. These results then provide the basis for an intuitive understanding of the different responses of the various media structures considered, and indicate why the achievable bit density for a given magnetic material may be greater in one design than another.

III. RESULTS AND DISCUSSION

When the read power available is sufficiently low for thermal effects to be unimportant, we showed in earlier work[1] that an optimum quadrilayer structure provided maximum signal-to-noise ratio at a fixed read-beam power during readout in a magneto-optical system. The design of the device is shown in Fig. 2. The magnetic thin film lies between two transparent dielectric films that together rest on an opaque reflector, and the whole is supported by a glass substrate. In later work,[2] we took the first steps toward determining how the structure could be adjusted to make best use of the laser power available for the read and write processes and showed that considerable gains in signal-to-noise could be expected by detuning the optimum device in such a way that all the laser power available would be used for recording. The effects of detuning on the signal-to-noise were then more than made up for by the extra power that could be used during readout. In the following we will put this result on a quantitative basis.

The details of the media designs considered and the optical and thermal parameters used in the calculations for a wavelength of 840 nm are shown in Tables I and II, respectively. The quadrilayer designs themselves fall into two categories: the first representing optimum designs, in the sense of providing maximum signal-to-noise ratios at fixed laser power when heating during readout can be ignored, and the second representing sub-optimum situations but providing what we shall see are attractive thermal characteristics. The signal-to-noise ratio at the same fixed, small laser power, however, is only slightly different in the two cases (Δ SNR < 0.5 dB) and therefore any major differences in performance in a magneto-optical recording system will derive directly from different thermal characteristics. It therefore follows that the power required for a fixed temperature rise under continuous illumination will be a direct relative measure of the readout signal-to-noise for a given quadrilayer structure. Similarly, the power required for a fixed temperature rise under pulsed illumination will be a direct relative measure of the writing sensitivity at fixed applied magnetic field.

Figures 3 and 4 then show respectively the power required to raise the temperature of the magnetic medium by 100 °C during readout and writing versus the velocity of the medium for each of the structures. At the simplest level, the behavior for each structure is as expected—more power is needed for readout at fixed maximum temperature and for writing at fixed resolution as the medium velocity is increased. However, at the next level, an interesting effect can be seen, namely the rate of power increase is larger for writing than for reading, a result of considerable value when selecting a medium for a particular system. Moreover, different structures are seen to require very different power levels. In the remainder of this section, we will trace the origin of these effects and establish the conditions under which a particular structure would provide the best performance in a magneto-optical system.

The structure with greatest writing sensitivity (structure a) is an optimum quadrilayer with dielectric reflector. However, it also tolerates least power in readout, and therefore its selection as the medium of choice in a magneto-optical recording system would be appropriate in the case of an insensitive magnetic material or of severely limited laser power. For magnetic materials of current interest[10] and in view of the present availability of power from solid-state lasers, it is likely that neither of these conditions will pertain. It is important to note, however, that the thermal characteristics of the equivalent bilayer structure, i.e., a 20-nm-thick magnetic film on a glass substrate overcoated with a 100-nm-thick dielectric film, are obtained directly from these particular quadrilayer results by correcting for the smaller absorptance at the bilayer. In this case, there is an increased in the writing power by a factor of about 2. While there is a corresponding renormalization of the readout curve, the signal-to-noise actually achieved at the increased read beam power allowed remains unchanged because of the lower intrinsic signal-to-noise ratio of the bilayer devices. Nevertheless, these results do demonstrate that this simplest of realizable magneto-optic structures might be a sufficient magneto-optical medium, particularly in lower performance memories.

When the dielectric reflector is replaced by an aluminum one, the power levels for the readout and writing curves

TABLE I. Design of quadrilayers.[a]

Quadrilayer label	Over	Layer thickness (nm) Magnetic	Intermediate	Reflecting
Optimum:				
a	100	20	60	Thick (Dielectric)
b	100	20	60	50 (Aluminum)
c	310	20	60	50 (Aluminum)
d	100	20	60	Thick (Aluminum)
Detuned:				
e	100	20	30	50 (Aluminum)
f	100	20	30	Thick (Aluminum)

[a] All the optimum quadrilayers have the same signal-to-noise ratio for fixed system parameters. Under equivalent circumstances the detuned structures have a signal-to-noise that is at most 0.5 dB lower.

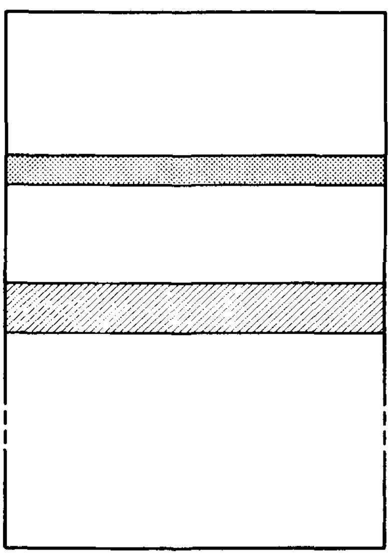

FIG. 2. A schematic representation of the quadrilayer configuration. The thicknesses of the reflector (hatched), intermediate layer, magnetic film (shaded), and overlayer may be adjusted to match the write sensitivity to a given magneto-optical system and thus obtain best readout signal-to-noise.

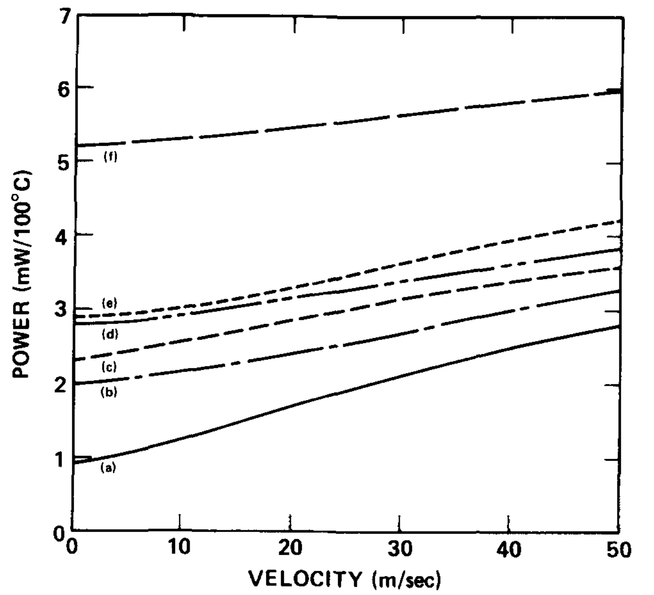

FIG. 3. Power (cw) required during readout to heat the magnetic film by 100 °C (peak of temperature distribution) vs medium velocity for the quadrilayer structures of Table I.

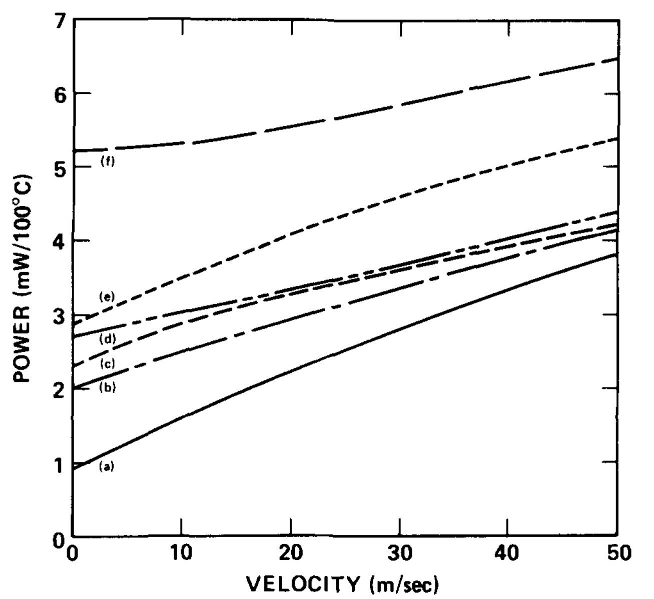

FIG. 4. Power (pulsed with duration r_0/V) required during writing to heat the magnetic film by 100 °C (peak of temperature distribution) vs medium velocity for the quadrilayer structures of Table I.

TABLE II. Optical and thermal parameters of materials.

Material		Refractive index 840 nm	Specific heat (J/cm^3/deg)	Heat conductivity (J/cm/deg/sec)
Glass substrate		1.5	2.0	0.015
Magnetic layers		3.67 + 3.85i	3.2	0.4
Over/intermediate layers		2.0	2.0	0.015
Reflector:	Aluminum	2 + 7.1i	2.7	2.4
:	Dielectric	2 + 7.1i[a]	2.0	0.015

[a] It is sufficient to use an effective refractive index for the dielectric reflector in this work since we are mainly concerned with the effects of heat flow toward the substrate.

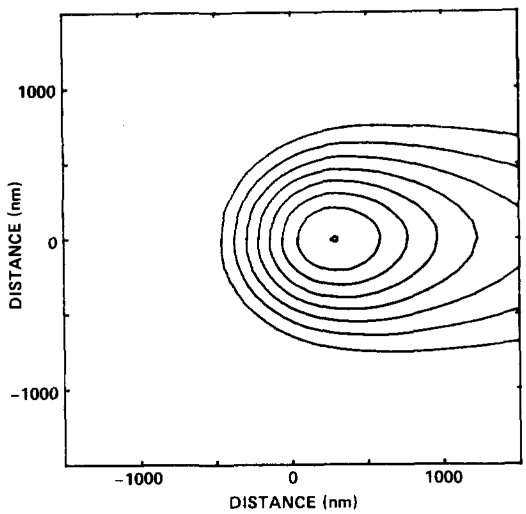

FIG. 5. Steady-state isotherms in the magnetic film of quadrilayer (a) of Table I when the medium moves at 20 m/S from the left to right relative to the beam. The central maximum is at 57.6 °C/mW, and each successive contour represents a temperature that is lowered by 10% of the maximum.

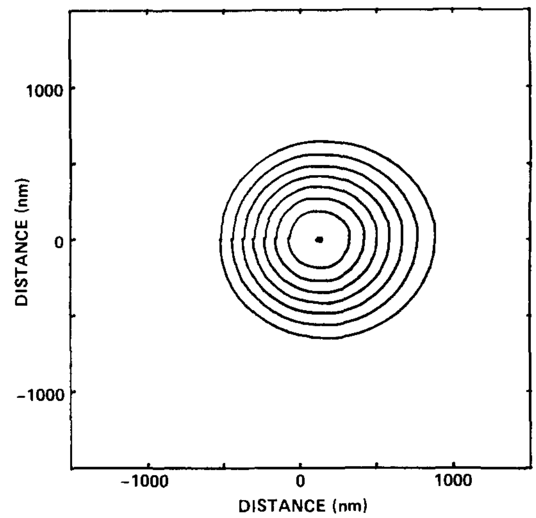

FIG. 7. Steady-state isotherms in the magnetic film of quadrilayer (d) of Table I when the medium moves at 20 m/S from left to right relative to the beam. The central maximum is at 31.4 °C/mW, and each successive contour represents a temperature that is lowered by 10% of the maximum.

increase progressively with aluminum thickness to provide one satisfactory way of adjusting the quadrilayer structure to the pertaining system writing constraints. For example, at a medium speed of 20 m/S, a decrease of writing sensitivity by a factor of about 1.5 leads to an increase in readout signal-to-noise at the read beam power now allowed of about 3 dB when the dielectric mirror is replaced by thick aluminum. These effects of course are caused by increased heat flow to the aluminum sink, and the isotherms for the magnetic layer shown in Figs 5, 6, and 7 make this very apparent. Namely, when heat flow to the substrate is minimized by using the dielectric reflector, a significant part of the heat generated in the magnetic film must be lost by lateral flow. Thus is Fig. 5, the maximum temperature in the magnetic film is displaced downstream from the center of the laser spot, and a long tail

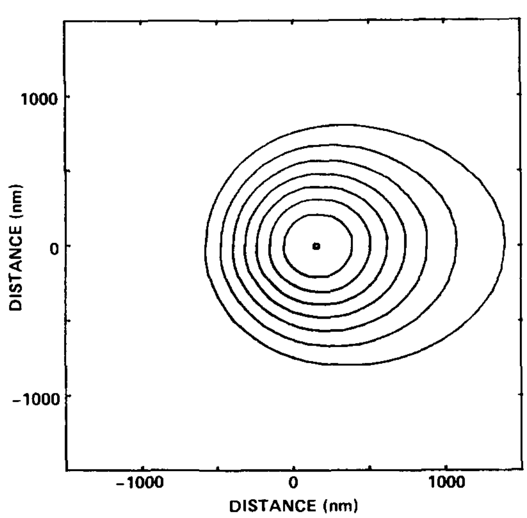

FIG. 6. Steady-state isotherms in the magnetic film of quadrilayer (b) of Table I when the medium moves a 20 m/S from left to right relative to the beam. The central maximum is at 41.5 °C/mW, and each successive contour represents a temperature that is lowered by 10% of the maximum.

is apparent in the temperature distribution. However, as heat flow toward the substrate is increased in Figs. 6 and 7 by replacing the dielectric mirror with an aluminum layer and by increasing the aluminum layer thickness, the temperature distributions tend to move toward the original Gaussian intensity distribution of the laser spot. Note in particular the disappearance of the downstream tail and the movement of the temperature maximum toward the center of the laser beam. This is an important result because it demonstrates that heat coupling toward the substrate can be made large enough to overcome the enlarging effects of lateral heat flow on bit size that may occur during writing. For high performance memories, this factor may be of considerable value.

Further control of the thermal characteristics of the quadrilayer structure may be obtained by adjusting the overlayer thickness. If this is increased discretely in half-wave steps, the quadrilayer maintains its optimum response but now requires more power for writing. Figures 3 and 4 show the effects of a half-wave increase in the overlayer thickness when a 50-nm-thick aluminum layer is used as reflector (structure c). Fortuitously, the writing and reading results are now very similar to those for the structure with a 100-nm-thick overlayer and relatively thick aluminum reflector. A combination of overcoat and reflector thickness adjustments can therefore yield optimum results under certain circumstances.

Finally, structures requiring the highest write powers and therefore providing the largest signal-to-noise in readout are obtained by decreasing the intermediate layer thickness to create a detuned design. Two examples using an intermediate layer thicknesses of 30 nm and different aluminum reflecting layer thickness are shown in Figs. 3 and 4 as curves e and f. As before, increases in write power and readout signal are evident when the aluminum layer thickness is increased, but now the media and system can be matched over a much larger range. For example, if sufficient laser power is available for writing when the medium travels at 20 m/S, the signal-to-noise attainable with the increased read-beam power now allowed for the detuned quadrilayer structure that employs a thick aluminum reflector, is about 2 dB greater than that possible for the equivalent optimum structure. In this case, the write power required at fixed applied magnetic field is about 1.7 times greater.

There is a common link in all of these trends. As the thermal coupling to the aluminum heat sink is improved, the time constant for attaining the pseudosteady state decreases. The temporal difference between the writing and reading processes therefore gets smaller and indeed has almost disappeared in the most detuned structure (cf. curves f in Figs. 3 and 4). If thermomagnetic writing can still be achieved satisfactorily, in this condition then both the signal-to-noise in readout and the domain resolution are simultaneously maximized.

IV. CONCLUSIONS

We have described how the basic optimum quadrilayer structure can be adjusted to match its recording needs to those of a particular system in such a way as to maximize the readout signal-to-noise and obtain maximum recording density. In all of this, we assumed that recording was carried out in a fixed applied magnetic field. While this is reasonable for the discussion presented, it is an unlikely constraint in practice. That is, the writing characteristics of a given material depend both on laser power and applied magnetic field such that two media structures with different thermal characteristics could, for example, be written as well with the same laser power and different applied magnetic fields, as with different laser powers and the same applied magnetic field. A system designer, therefore, should first consider the least thermally sensitive quadrilayer design prior to any other because of its highest signal-to-noise in readout and then compensate for lack of writing sensitivity by using a higher applied magnetic field. If this approach proved technologically unfeasible or economically unsound with the available magnetic material, then he can follow the systematic approach outlined here to obtain the media structure that provides the best compromise between the writing and reading constraints of the magneto-optical system. While this is a long procedure which must be done at each spin speed, for instance, it nevertheless represents a completely tractable problem.

ACKNOWLEDGMENT

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