MULTI WAVELENGTHS READ-OUT FOR MULTI-VALUED MO RECORDING

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Abstract - We propose a new multi wavelengths read-out method which solves the fatal problem of decreasing the signal to noise ratio (SNR) in multi-valued magneto-optical (MO) recording. Theory and method to find the optimal condition are discussed and the two examples for the disks of RE-TM films and the combination of RE-TM and magnetic garnet films are investigated. This method provides theoretically 12.5 dB higher SNR than conventional one, and is suitable to realize 3-dimensional MO recording with the combination of the multi-valued MO recording proposed by Ohta and Shimazaki et al.[1]

KEYWORDS: MULTI-VALUED, MULTI-WAVELENGTHS, READ-OUT, MAGNETO-OPTICAL RECORDING, 3-DIMENSIONAL RECORDING, SIGNAL TO NOISE RATIO

INTRODUCTION

For achieving super high density magneto-optical (MO) disk, media for shorter wavelengths[2] and the magnetically induced super resolution (MSR)[3] were investigated. As one of the other approaches, the volumetric optical disk[4] as shown in Fig. 1 has been investigated 10 years ago. The disk has several memory layers and the data were individually recorded in each layer. It has been proved to be the potential candidate for high capacity recording in CD-ROM[5] as SD scheme. However, this volumetric optical disk for rewritable recording media was not realized, because the higher writing laser power was required. The energy loss was larger than the conventional MO disk, because the laser beam should pass through the several layers to access the memory layer. Additionally, a high numerical aperture lens was required for the system of the volumetric optical disk.

Ohta and Shimazaki et al.[1] reported the novel method for multi-valued MO recording as shown in Fig. 2. Data are individually written in each memory layer without changing the focal point. The all memory layers are settled within the depth of focus. The memory layer to be written is selected by choosing both amplitude and direction of the external bias field. By using this method, the 4 levels of the read-out signal were detected as shown in Fig. 3.[1]

The amplitude of read-out signal is decreasing with increasing of number of signal levels. For example, a double-layer 4-level read-out system is
considered. For the conventional 2-level read-out, the amplitude of MO read-out signal is denoted by \( A_{0-p} \) and \( A_{p-p} \) which correspond to zero to peak and peak to peak values of read-out signal, respectively, as shown in Fig. 4(a). Under the same value of \( A_{p-p} \), SNR is reduced by 9.5 dB for the case of 4-level read-out as shown in Fig. 4(b). With increasing of number of signal levels, the amplitude of read-out signal is essentially decreasing. To solve this fatal issue, we propose a new multi-wavelength read-out method for the multi-valued MO recording.

**MULTI-WAVELENGTH READ-OUT METHOD**

The schematic representation of multi-valued MO disk which is composed of several recording layers \((i=1,2,...,k,...,n)\) and is being read by different wavelengths is shown in Fig. 5. The directions of magnetic moment in \(k\)-th MO layer are denoted by \(X_k = \pm 1\) corresponding to up or down to the film normal, respectively. When the laser beam wavelength is \(\lambda_j\), the reflection coefficient of the whole film resulting from optical interference is defined as \(R_j\). The total Kerr rotation angle \(\theta_j\) of the reflected light is a function of \(X_i\) \((i=1,2,...,n)\). \(\theta_{kj}\), which shows a difference in \(\theta_j\) when only a \(X_k\) has been changed its direction, is defined by the following eq. (1).

\[
2\theta_{kj} = \theta_j(X_1, X_2, ..., X_k=+1, ..., X_n) - \theta_j(X_1, X_2, ..., X_k=-1, ..., X_n)
\]

(1)

In the case of \(n=2\), it is theoretically proved by expanding \(\theta_{kj}\) using the virtual optical constant method \(^6\) that \(\theta_{kj}\) is independent from \(X_i\) \((i\neq k)\). For the case of \(n \geq 3\), \(\theta_{kj}\) depends on \(X_i\) \((i\neq k)\). However, since the difference between the refractive indices \(n_+\) and \(n_-\) (which are indices for right handed and left handed circular polarized light, respectively) of each layer is extremely smaller than the refractive index for non-polarized light, it is derived that \(\theta_{kj}\) is approximately independent from \(X_i\) \((i\neq k)\). It means that \(\theta_j\) becomes a linear combination of \(\theta_{kj}\). Since the detected signal \(D_j\) is proportional to the \(R_j\theta_{kj}\), \(D_j\) can be deduced by eq. (2).

\[
D_j = \sum_{k=1}^{n} R_j \theta_{kj} X_k
\]

(2)

Then, if signals are detected at several wavelengths as \(\lambda_1, \lambda_2, ..., \lambda_n\) corresponding \(D_1, D_2, ..., \)

\[\text{Fig. 3. The read-out waveform of the multi-valued MO disk.} \]
Dn signals will be derived by eqs. (3) and (4).

\[ S_{kj} = R_j \theta_{kj} \]  
\[ \begin{pmatrix} D_1 \\ D_2 \\ D_n \end{pmatrix} = \begin{pmatrix} S_{11} & S_{21} & \cdots & S_{n1} \\ S_{12} & S_{22} & \cdots & S_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ S_{1n} & S_{2n} & \cdots & S_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} \]  

By using the inverse matrix of S parameters, \( X_i \) is determined by \( D_j \) \( (j = 1, 2, \ldots, n) \). In the case of \( n = 2 \), \( X_1 \) and \( X_2 \) are determined by eq. (5).

\[ \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{21} \\ S_{12} & S_{22} \end{pmatrix}^{-1} \begin{pmatrix} D_1 \\ D_2 \end{pmatrix} \]  

Therefore, \( X_1 \) and \( X_2 \) can be detected from \( D_1 \) and \( D_2 \) by using a recombination circuit as shown in Fig. 6 according to eq. (5).

**SNR FOR THE MULTI-WAVELENGTH READ-OUT METHOD**

While \( X_i \) is determined by \( D_j \) according to eq. (4), the noise is also combined by the recombination circuit. The case for \( n = 2 \) was investigated, for example. The noise generated in optical detectors and amplifiers has to be taken into account by adding noise \( n_1 \) and \( n_2 \). Then the outputs of the recombination circuit are including additional noise of which root-mean-square (r.m.s.) values are \( X_{n1} \) and \( X_{n2} \), respectively. Let the power of \( n_1 \) and \( n_2 \) be \( P_{n1} \) and \( P_{n2} \), respectively. Under the assumption that the noise \( n_1 \) and \( n_2 \) are correlation free each other, and the impedance of the detecting circuit is \( Z \), \( X_{n1} \) and \( X_{n2} \) are shown in eqs. (6) and (7) as follows.

\[ X_{n1} = \sqrt{\frac{S_{23} P_{n1} + S_{13} P_{n2}}{\Delta}} \]  
\[ X_{n2} = \sqrt{\frac{S_{13} P_{n1} + S_{23} P_{n2}}{\Delta}} \]  

where \( \Delta = |S_{11} S_{22} - S_{12} S_{21}| \)  

Under the assumption that the power \( P_{n1}, P_{n2} \) are the same \( (P_{n1} = P_{n2}) \) and the r.m.s values of noise \( n_1 \) and \( n_2 \) are defined as \( N_{rms} = \sqrt{Z P_{n1}} = \sqrt{Z P_{n2}} \), \( X_{n1} \) and \( X_{n2} \) are shown in eqs. (9) and (10).

\[ X_{n1} = N_{rms} \frac{\sqrt{S_{23}^2 + S_{13}^2}}{\Delta} \]  
\[ X_{n2} = N_{rms} \frac{\sqrt{S_{13}^2 + S_{23}^2}}{\Delta} \]  

\[ SNR_{x1} = \frac{|X_1/X_{n1}|}{SNR_{x2} = |X_2/X_{n2}|} \]  

are defined by eqs. (11) and (12).

\[ SNR_{x1} = \frac{1}{N_{rms}} \frac{\Delta}{\sqrt{S_{23}^2 + S_{13}^2}} \]  
\[ SNR_{x2} = \frac{1}{N_{rms}} \frac{\Delta}{\sqrt{S_{13}^2 + S_{23}^2}} \]  

The quality factors of the \( X_1 \) and \( X_2 \) are defined by eqs. (13) and (14), and are proportional to \( SNR_{x1} \) and \( SNR_{x2} \) under the condition that the \( N_{rms} \) is constant.

\[ QF_1 = \frac{\Delta}{\sqrt{S_{23}^2 + S_{13}^2}} \]  
\[ QF_2 = \frac{\Delta}{\sqrt{S_{13}^2 + S_{23}^2}} \]  

![Fig. 6](image_url)  

**Fig. 6** The schematic diagram of the circuit for the recombination for multi-wavelength read-out method without noise generated in optical detectors and amplifiers.

![Fig. 7](image_url)  

**Fig. 7** The schematic diagram of the circuit for the recombination for multi-wavelength read-out method with noise generated in optical detectors and amplifiers.
For getting high SNR for both $SNR_{X1}$ and $SNR_{X2}$, both $QF_1$ and $QF_2$ should simultaneously become large values. Therefore, the quality factor for both $X_1$ and $X_2$ is defined by the product of $QF_1$ and $QF_2$ as shown in eq. (15).

$$QF = QF_1 \times QF_2$$

(15)

For the purpose of finding the optimal condition which leads to the maximum SNR, $QF_1$, $QF_2$ and $QF$ are calculated under the wide variety of $S$ parameters. The theoretical increase in SNR for the specific conditions is shown in Table 1.

For the case 1: $S_{11} = S_{22} = a$, $S_{12} = S_{21} = 0$, the schematic diagram of the wavelength dependence of $S$ parameters is shown in Fig. 8(a). In this case, $QF_1$ and $QF_2$ directly depend on "a" itself, and $SNR_{X1}$ and $SNR_{X2}$ are equal to the conventional 2-level read-out method in which the read-out signal is proportional to "a".

For the case 2, which leads to the theoretical maximum of $QF_1$ and $QF_2$, $S$ parameters should meet the ideal condition such as $S_{11} = -S_{22} = S_{12} = S_{21}$. The schematic diagram of the dependence of $S$ parameters on the wavelengths for this ideal case is also shown in Fig. 8(b). It means that the effective magneto-optical effect at the different wavelengths must keep its magnitude, however, differ in the sign between $S_{11}$ and $S_{22}$ oppositely. Under this condition, $QF_1$ and $QF_2$ are equal to $\sqrt{2}a$, and are 3 dB larger than those of the case 1.

### SNR COMPARED WITH CONVENTIONAL 4-LEVEL READ-OUT METHOD

As mentioned in the previous section, $SNR_{X1}$ and $SNR_{X2}$ under the case 1 are equal to SNR of the 2-level read-out method. When the signal $A_{0-p}$ for the 2-level read-out method as shown in Fig. 4(a) is "a", SNR of the conventional 4-level read-out method ($SNR_{conv}$) is 9.5 dB smaller than that of the 2-level read-out method, because $SNR_{conv}$ for the 4-level read-out method is defined by eq. (16) as shown in Fig. 4(b).

$$SNR_{conv} = \frac{a/3}{N_{max}}$$

(16)

Therefore, $SNR_{X1}$ and $SNR_{X2}$ in the case 1 are 9.5 dB larger than $SNR_{conv}$. For the case 2, $SNR_{X1}$ and $SNR_{X2}$ are 12.5 dB larger than $SNR_{conv}$, because $QF_1$ and $QF_2$ for the case 2 are 3 dB larger than those of the case 1 as shown in Table 1.

### DESIGN FOR MULTI-LAYER FILM FOR MULTI-WAVELENGTH READ-OUT

The effect of the multi-wavelength read-out method on SNR is clarified by eqs. (11)-(12). To reveal the optimal materials and stacking of films for achieving high SNR of the multi-wavelength read-out method, SNR for TbFeCo/garnet/substrate and PtCo/TbFeCo/SiN/TbFeCo/SiN/substrate are investigated.

Table 1 The quality factor $QF_1$ and $QF_2$ for the specific conditions, $a$ is a constant.

<table>
<thead>
<tr>
<th>Case</th>
<th>$(S_{11}S_{22})$</th>
<th>$QF$</th>
<th>$QF/QF_{case1}$</th>
<th>$SNR/SNR_{conv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$(a, 0)$</td>
<td>$a$</td>
<td>$a$</td>
<td>$+9.5$</td>
</tr>
<tr>
<td></td>
<td>$(0, a)$</td>
<td>$a$</td>
<td>0</td>
<td>$+9.5$</td>
</tr>
<tr>
<td>2</td>
<td>$(a, -a)$</td>
<td>$\sqrt{2}a$</td>
<td>$\sqrt{2}a$</td>
<td>$+3$</td>
</tr>
<tr>
<td></td>
<td>$(a, a)$</td>
<td>$2a$</td>
<td>$2a$</td>
<td>$+12.5$</td>
</tr>
</tbody>
</table>

Fig. 8. The schematic presentations of the dependence of $S$ parameters on the wavelengths for the case 1 and the case 2 in Table 1.
TbFeCo/garnet/substrate (case 3)

For getting high signal levels from all MO layers, high optical transparency for MO layer is required. The double-layer film which consists of garnet for the under layer and TbFeCo for the upper layer as shown in Fig. 9 is investigated. Since the garnet has a high transparency, the power of the incident light can reach the TbFeCo film without much energy loss, and the reflected light from TbFeCo film can be also detected with less energy loss. Thus, the signals from both garnet and TbFeCo films are large. Since the Faraday rotation angle of the garnet is large, the garnet film is one of the good candidate for the multi-wavelength read-out method.

S parameters are estimated for $\lambda_1 = 515 \text{ nm}$ and $\lambda_2 = 780 \text{ nm}$. The parameters for the calculation is shown in Table 2. The dependencies of the S parameters on the thickness of the garnet film for $\lambda_1 = 514 \text{ nm}$ and $\lambda_2 = 780 \text{ nm}$ are shown in Figs. 10 and 11, respectively. Since the extinction coefficient of the garnet is small, the decreases in the signals from the upper layer ($S_{21}$ and $S_{22}$) with increasing the thickness of garnet film are small. For 100 nm in thickness of garnet film, $S$ parameters are $S_{11} = 0.25$, $S_{12} = 0$, $S_{21} = 0.18$, $S_{22} = 0.22$ as shown in the case 3 in Table 3. SNR and SNR are 7.3 and 8.4 dB larger than SNR for $\alpha = 0.25$ (= $S_{11}$).

PtCo/TbFeCo/SiN/TbFeCo/SiN/substrate (case 4)

The $S$ parameters for MO disk of the multi-valued MO recording as shown in Fig. 2 are evaluated for $\lambda_1 = 680 \text{ nm}$ and $\lambda_2 = 780 \text{ nm}$. The difference of $S$ parameters is caused by the optical interference of the whole films of SiN, TbFeCo and PtCo, while there is almost no difference of the refractive indices of TbFeCo between $\lambda_1 = 680 \text{ nm}$ and $\lambda_2 = 780 \text{ nm}$. For searching the thickness of the dielectric layers which leads high SNR for the multi-wavelength read-out method, quality factor $Q_F$ is evaluated as functions of the thickness $t_1$ of the 1st layer (SiN) and the thickness $t_3$ of 3rd layer (SiN) under the variety of the thickness of TbFeCo layer.

$Q_F$ as functions of $t_1$ and $t_3$ under the condition that the thicknesses of the 2nd layer (TbFeCo), the 4th layer (TbFeCo) and the 5th layer (PtCo) are 8, 20 and 200 nm, respectively, is shown in Fig. 12.

The dependence of $Q_F$ on $t_3$ is strong, while the dependence of $Q_F$ on $t_1$ is weak. For one of the
local maxima of $QF$: $t_1 = 20$ nm and $t_3 = 180$ nm. S parameters are as follows: $S_{11} = 0.15$, $S_{12} = 0.065$, $S_{21} = 0.028$ and $S_{22} = 0.13$ as shown in the case 4 in Table 3. Comparing $SNR_{conv}$ (for $a = 0.25$), $SNRX_1$ and $SNRX_2$ are 4.1 and 2.3 dB larger than $SNR_{conv}$, respectively. Thus, SNR is increased by using the multi-wavelength read-out method, while the signal amplitude of this disk is smaller than that of the disk consisting of the garnet film.

Table 3 S parameters and SNR for the case 3: TbFeCo/garnet/substrate and the case 4: PtCo/TbFeCo/SiN/TbFeCo/substrate.

<table>
<thead>
<tr>
<th>case</th>
<th>$S_{11}$</th>
<th>$S_{21}$</th>
<th>$S_{12}$</th>
<th>$S_{22}$</th>
<th>$SNR/\overline{SNR}_{conv}$[dB]</th>
<th>$SNRX_1$</th>
<th>$SNRX_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.25</td>
<td>0.18</td>
<td>0</td>
<td>0.22</td>
<td>7.3</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.15</td>
<td>0.028</td>
<td>0.065</td>
<td>0.13</td>
<td>4.1</td>
<td>2.3</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 12 The dependence of the $QF$ on the thicknesses of the 1st layer and 3rd layer under the condition that the thicknesses of the 2nd layer (TbFeCo), the 4th layer (TbFeCo) and the 5th layer (PtCo) are 8, 20 and 200 nm, respectively.

CONCLUSION

To solve the fatal problem of the decrease in SNR for the multi-valued MO recording, we propose the new multi-wavelength read-out method. It is revealed that the theoretical maximum of SNR is 12.5 dB larger than that of the conventional multi-valued recording method. For the case of the multi-layer film made by garnet and TbFeCo at $\lambda_1 = 515$ and $\lambda_2 = 780$ nm, SNR derived from the optical parameters are 7.3 and 8.4 dB larger than $SNR_{conv}$. For the case of PtCo/TbFeCo/SiN/TbFeCo/SiN at $\lambda_1 = 680$ and $\lambda_2 = 780$ nm, by choosing optimal thickness for SiN layers for interference, it is shown that SNR are 4.1 and 2.3 dB larger than $SNR_{conv}$, respectively. We provide the method to choose the optimal condition, and it is useful for achieving a new high performance 3-dimensional MO memory system. We are now investigating the influence on the writing properties of the $S$ parameters. Additionally, we are also preparing the optical head for the multi-wavelength approach.

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