Analysis of differential phase detection signal of a novel multi-level read-only disc

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To improve the tracking servo performance, a novel signal waveform multi-level (SWML) read-only disc realized on the digital versatile disc (DVD) platform is presented. The characteristic of the differential phase detection (DPD) signal of the SWML read-only disc is analyzed both in theory and experiment. The amplitude of the DPD signal of the SWML read-only disc in an open tracking servo loop is about 2/3 of that of the DVD read-only disc. The uniformity and symmetry of the DPD signal of the SWML read-only disc are similar to those of the DVD read-only disc and better than the former multi-level run-length limited (ML-RLL) read-only disc.

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As the fast-growing market for high-definition television (HDTV) broadcasting, the optical disc with larger capacity and higher data transfer rate is required[1]. Multi-level (ML) method, one of the technologies to increase the storage capacity, can record more than two states in one mark without changing the optical and mechanical units. Run-length limited (RLL) modulation codes are widely used in the conventional optical discs which can effectively improve the record density. Combining ML method and RLL modulation codes, ML-RLL method can achieve equivalent storage density with less level than only using ML method[2−5]. Zhang *et al.* proposed the implementation of the four levels (2, 10) constrained RLL recording on the digital versatile disc (DVD) read-only disc[4].

The differential phase detection (DPD) signal is the input signal for the tracking servo control loop, which is used to keep the focused laser beam always in the center of the track to generate the radio frequency (RF) signal. The ML-RLL read-only disc mentioned above is realized by changing the width and depth of the recording marks which is called amplitude modulation. However, influenced by the variation of the recording marks, the uniformity and symmetry of the DPD signal of the ML-RLL read-only disc are worse than that of the DVD read-only disc, which result in the instability of the tracking servo[6]. Therefore, it is more difficult to design the tracking servo controller for this type of ML-RLL read-only disc to obtain sufficient robustness.

In this letter, to improve the tracking servo performance, a novel ML read-only disc using signal waveform (SW) modulation is presented and called SWML read-only disc. Conventional DVD read-only disc uses the pits/lands to generate the readout signal. In the SWML read-only disc, the sub-lands/sub-pits are inserted into the pit/land, as shown in Fig. 1. By inserting the sub-lands/sub-pits in the different positions of the conventional pits/lands or changing the length or depth of the sub-land/sub-pit, readout signals with different waveforms can be generated, indicating different levels. Figure 2 shows the atomic force microscopy (AFM) photomicrographs of the pit pattern of the conventional DVD read-only disc and the SWML read-only disc. It can realize more levels on the longer pits/lands because the sub-lands/sub-pits can be inserted into more positions and can vary more in both length and depth. To obtain high signal-to-noise ratio (SNR), the sub-lands/sub-pits are smaller than the shortest pit/land of DVD and inserted into the position near the middle of the pits/lands. Furthermore, there is no sub-land/sub-pit in the $3T$ or $4T$ pit/land (T is

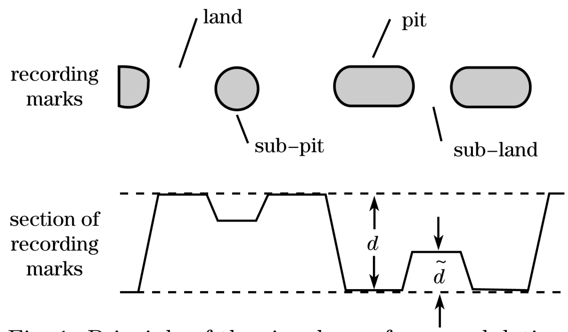

Fig. 1. Principle of the signal waveform modulation.

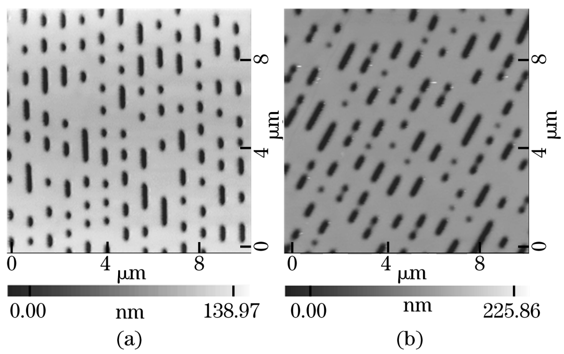

Fig. 2. AFM photomicrographs of (a) conventional DVD read-only disc and (b) SWML read-only disc.

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the channel clock length) owing to its small optical readout signal. Another advantage of the SWML read-only disc is that the DPD signal is similar with the conventional DVD read-only disc and the tracking servo performance is better than the former ML-RLL read-only disc.

In the high density optical read-only disc, the DPD method is widely used for generating the tracking error signal (TES). The theory of the DPD method can be referred to Braat's[7]. The TES can be detected by the phase difference of the photocurrent from the four-quadrant photodetector (PD) and the amplitude of the DPD signal $\mathrm{TES_{DPD}}$ can be expressed as

$$\mathrm{TES_{DPD}} \propto \mathrm{phase}(i_a + i_c) - \mathrm{phase}(i_b + i_d), \quad (1)$$

where i_a, i_b, i_c, and i_d are the photocurrents of the four quadrants of the PD and phase$(\cdot)$ is the phase of the signal.

The original readout model of the optical disc was built by Hopkins on the basis of the scalar diffraction theory and then improved by Milster *et al.*[8−10] The characteristic of the DPD signal can be simulated by the model of the optical disc as shown in Fig. 3. The amplitude distribution of the incident light at the exit pupil of the object lens can be expressed as

$$u_{\mathrm{I}}(x,y) = \exp\left(-\sigma \cdot \frac{x^2+y^2}{2}\right) \cdot \exp\left[2\pi \mathrm{i} \cdot \omega(x,y)\right], \quad (2)$$

where σ is the Gaussian factor, $\omega(x,y)$ is the wave aberration function caused by the object lens, and (x,y) is the coordinates normalized with the pupil radius. In the SWML disc model, a sub-land is inserted into the pit. Then the disc reflectivity function of the pit can be expressed as

$$R(X,Y) = \begin{cases} \exp\left(2\pi \mathrm{i} \cdot 2n\dfrac{d}{\lambda}\right), & (X,Y) \in S \\ \exp\left(2\pi \mathrm{i} \cdot 2n\dfrac{d-\tilde{d}}{\lambda}\right), & (X,Y) \in \tilde{S} \\ 1, & \text{otherwise} \end{cases}, \quad (3)$$

where d is the geometric depth of the pit, $\tilde{d}$ is the geometric depth of the sub-land, S is the range of the pit, $\tilde{S}$ is the range of the sub-land, and n is the refractive index of the layer of the disc. The amplitude distribution of the reflected light at the exit pupil can be expressed as

$$u_{\mathrm{O}}(x,y) = u_{\mathrm{I}}(x,y) \otimes r(x,y), \quad (4)$$

where $\otimes$ is two-dimensional (2D) convolution and $r(x,y)$ is the 2D Fourier transformation of $R(X,Y)$. Then the reflected light falls on the 4-quadrant PD and the photocurrent I_i on each quadrant of the PD can be expressed as

$$I_i = \iint_{Q_i} k|u_{\mathrm{O}}(x,y)|^2 \mathrm{d}x\mathrm{d}y, (x,y) \in Q_i, \quad (5)$$

where k is the sensitivity of the PD and Q_i is the scan range of each quadrant of the PD.

Using the above calculation model, the numerical simulation is made to analyze the effects of signal waveform modulation on the DPD signal in the SWML read-only disc. Typical $8T$ pits with different depths of the $1.5T$ sub-land inserted are analyzed. The parameters of the simulated system are listed in Table 1. For simplicity of analysis, the sub-land is assumed to be inserted in the middle of the $8T$ pit.

Figure 4 shows the readout RF signal of $8T$ pits with different signal waveform modulations. Four depths of the sub-land, 0, $\frac{1}{2}d$, $\frac{2}{3}d$, and d, are calculated when the track error is 0. The pit with the sub-land depth of 0 denotes the conventional pit. By inserting different depths of the sub-land, the readout RF signals have different waveforms, meaning that the signal waveform modulation can achieve different levels of RF signal.

Figure 5 shows the relationship between the amplitude of the DPD signal and the track error for $\tilde{d} = 0, \frac{1}{2}d, \frac{2}{3}d$, and d. The amplitude of DPD also presents the phase shift of the photocurrent signal summation of the two diagonal PD quadrants. The amplitude of the DPD signal of each waveform is almost a linear function of the track error, so it can present the track error information. And all lines are point symmetry with the origin. However, the different waveforms have effects on the amplitude of the DPD signal. Under the condition of the same track error, the amplitude of the DPD signal decreases while the depth of the sub-land grows up. The maximum difference is less than $0.1T$ when the track error is within ±50 nm. The results show that the sub-land has no effect on the symmetry of the amplitude of the DPD signal and has little effect near the origin when the laser beam

Table 1. Parameters of Simulated System

Parameter	Symbol	Value
Wavelength	λ	650 nm
Numerical Aperture	NA	0.60
Refractive Index of the Layer	n	1.55
Track Pitch	p	740 nm
Channel Clock Length	T	133 nm
Pit Length	l	$8T$
Pit Width	w	250 nm
Pit Depth	d	120 nm
Sub-Land Length	$\tilde{l}$	$1.5T$
Sub-Land Depth	$\tilde{d}$	$0, \frac{1}{2}d, \frac{2}{3}d, d$

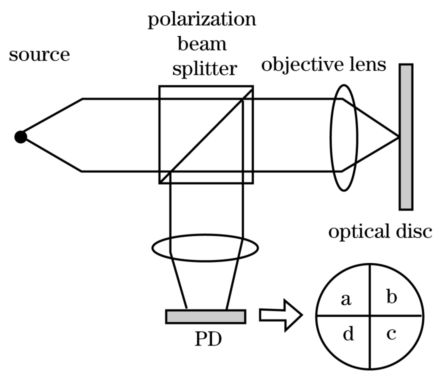

Fig. 3. Readout model of the optical disc.

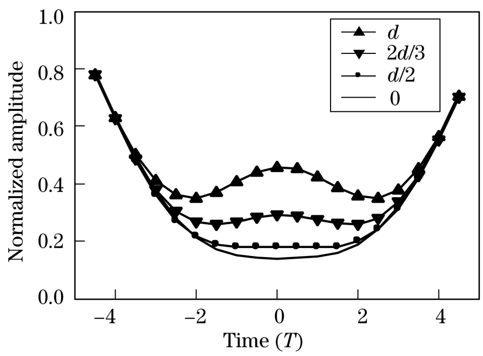

Fig. 4. Normalized amplitude of the readout RF signal for different depths of the sub-land.

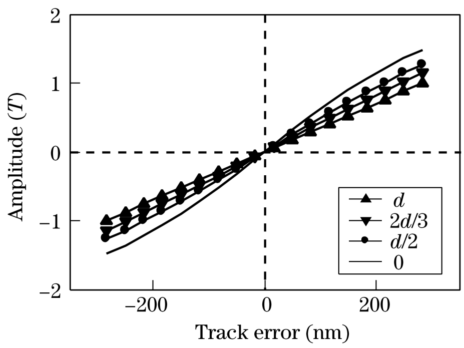

Fig. 5. Amplitude of the DPD signal versus the track error value for different depths of the sub-land.

crosses the center of the track. It is indicated that the waveform modulation has less effect on the DPD signal and may has better tracking servo performance.

The real DPD signal of the SWML read-only disc is also measured by the experiment and compared with those of the DVD read-only disc and the former ML-RLL read-only disc. The SWML read-only disc has the same wavelength of 650 nm, number aperture (NA) of 0.65, and track pitch of 740 nm as the conventional DVD read-only disc, so the optical readout system for the conventional DVD read-only disc can be applied in the experiment. The DPD signals of three types discs are measured by the same readout system when the focusing servo loop is closed and the tracking servo loop is open. Figure 6 shows the DPD signal of the DVD read-only disc, the ML-RLL read-only disc, and the SWML read-only disc. It can be found from the peak-to-peak amplitudes of the DPD signals that the former ML-RLL disc has a uniformity worse than the SWML read-only disc.

The DPD signals after crossing about 500 tracks of the three types discs were recorded for statistically analyzing the signal quantity. The mean value of the peak-to-peak amplitude of the DVD read-only disc is 2.02 while its variance is 0.010. For the former ML-RLL read-only disc, the two values are 1.37 and 0.061. And for the SWML read-only disc, they are 1.32 and 0.012, respectively. The amplitude of the DPD signal of the SWML read-only disc is about 2/3 of that of the conventional DVD read-only disc according to the experimental result, and the uniformity of the DPD signal of the

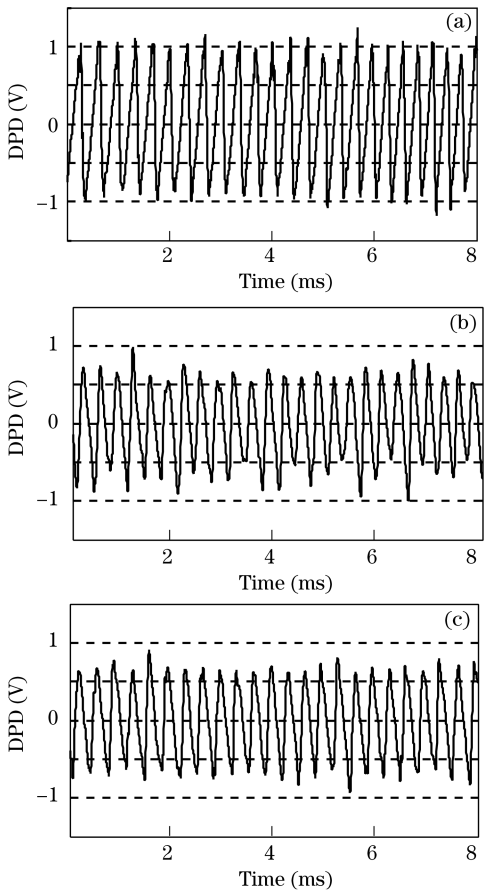

Fig. 6. DPD signals of (a) the DVD read-only disc, (b) the former ML-RLL read-only disc, and (c) the SWML read-only disc.

SWML read-only disc is similar to that of the conventional DVD read-only disc and better than that of the former ML-RLL read-only disc.

The asymmetry of the DPD signal is defined by

$$A = \left| \frac{T_1 - T_2}{T_1 + T_2} \right| \times 100\%, \qquad (6)$$

where T_1 and T_2 are the absolute positive and negative peak values of the DPD signal. The average asymmetry of the SWML read-only disc is about 3% while those for the conventional DVD read-only disc and the former ML-RLL one are about 4% and 21%, respectively. The symmetry of the DPD signal of the SWML read-only disc is similar to that of the conventional DVD read-only disc and better than that of the former ML-RLL read-only disc.

In conclusion, the characteristics of the DPD signal of the SWML read-only disc are analyzed. The simulation and experimental results show that the amplitude of the DPD signal of the SWML read-only disc in an open tracking servo loop is about 2/3 of that of the conventional DVD read-only disc, while the uniformity and symmetry of the DPD signal of the SWML read-only disc are similar to those of the conventional DVD read-only disc. Compared with the former ML-RLL read-only disc, the SWML read-only disc has better characteristics of the DPD signal, so it can achieve better tracking servo performance when the conventional DVD's tracking regulator with the lead-lag compensation method is employed.

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