Next-Generation Blue-Violet Laser Multi-Layer Optical Recording

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ABSTRACT

Multi-layer optical recording is a promising technology for increasing recording capacity using an optical pickup identical to that used for a single-layer optical disc. The objective for the next generation of blue-violet laser discs is the capability to record digital TV broadcasts and High-Definition TV programs. A capacity of 24 GB ~ 48 GB is targeted, equivalent to 2 ~ 4 hours' recording time.

In this paper, the feasibility of multi-layer recording for the next blue-violet generation is reviewed and physical formats applicable to multi-layer discs are discussed. The high-density approach using a blue-violet laser and a high NA objective lens with a thin cover layer is capable of achieving a capacity of 45 GB using a dual-layer structure and 90 GB using a quadruple structure; a DVD-compatible approach could achieve a capacity of 27 GB for a dual-layer structure and 54 GB for a quadruple-layer structure, based on the sawtooth wobble groove recording format.

Keywords: Optical disc, multi-layer recording, dual-layer recording, quadruple-layer recording, groove recording, blue-violet laser, phase-change recording, rewritable disc, write-once disc, DVD, HD-TV, thin cover layer.

1. INTRODUCTION

Recordable DVD (Digital Versatile Disc) discs with 4.7 GB capacity were launched onto the market in 2000[1]. However, there remains a constant demand for ever-increasing storage capacity. Promising technologies such as blue-violet lasers, high NA objective lenses, thin cover layers, super-resolution recording, and multi-layer recording are being urgently studied as means of improving recording capacity.

Multi-layer optical recording has great potential for increasing recording capacity using a conventional optical pickup, and is backward-compatible with single-layer optical discs with respect to reading and writing. Progress is being made in many directions in multi-layer optical recording, including in the so-called dual-layer DVD-ROM (Read-Only) disc[2], ROM/RAM (Rewritable) disc[3], WO (Write-Once)/WO disc[4], and RAM/RAM disc[5-6].

Table 1 shows examples of multi-layer optical discs designed so far.

Table 1 Multi-layer optical discs

	ROM	WO	RAM	RAM	WO
Layer	2	2	2	2	4
Capacity (GB)	8.5	5.2	8.5	45	90
Cover layer (mm)	0.6	0.6	0.6	0.1	0.1
Optics (λ/NA)	650 nm/0.60	680 nm/0.60	650 nm/0.60	405 nm/0.85	405 nm/0.85
Track addressing	Emboss pits	Header	Header	Sawtooth wobble	Sawtooth wobble
Speed (m/s)	3.49	6	6.3	5.1	5.1
Track pitch (µm)	0.75	0.75	0.615 (L&G)	0.32	0.32
Mark (µm)	0.40	0.62	0.42	0.206	0.206
Bit (µm)	0.267	0.41	0.28	0.129	0.129

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The first multi-layer optical disc, the dual-layer DVD-ROM disc (DVD-9, capacity 9 GB) was developed in 1995. Dual-layer DVD-based discs with WO/WO and RAM/RAM configurations were developed in 1997 and 1998 respectively.

Next-generation optical discs will be designed to record digital TV broadcasts and HD (High-Definition) TV programs. A one-hour HDTV digital recording requires a capacity of about 12 GB and a bit rate of about 25 Mbps. The capacity required for 2 ~ 4 hours of HDTV recording is likely to be 24 ~ 48 GB. Development of this capacity will depend on multi-layer recording.

In this paper a multi-layer phase-change recording technology for the next blue-violet generation is reviewed and discussed from the viewpoint of settling on a single format for ROM, WO, and RAM.

2. MULTI-LAYER OPTICAL RECORDING AND FORMAT DESIGN

2.1. ISSUES CONCERNING MULTI-LAYER RECORDING

Fig. 1 shows a schematic configuration of a dual-layer optical disc.

Layer 0 (L_0; nearest to the optical pickup) should show large optical changes between the amorphous and crystalline states and a high optical transmittance. Layer 1 (L_1; farthest from the optical pickup) requires high recording sensitivity.

Layer 0 should not interfere with the reproduced signal from Layer 1 or the write characteristics. The signal of Layer 1 may be disturbed by emboss headers and the recorded marks in the tracks of Layer 0. When an optical beam is focused on Layer 1, its spot diameter on Layer 0 becomes almost identical to the thickness of the intermediate layer. Therefore the optical beam crosses hundreds of tracks in Layer 0 and is diffracted by the embossed pits of the track headers.

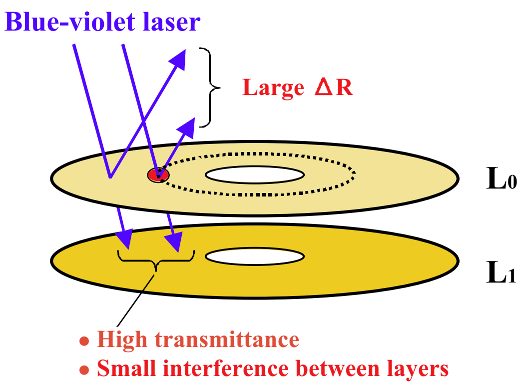


Fig.1 Schematic configuration of dual-layer disc

Fig. 2 shows how the RF signal of Layer 1 is affected by headers in Layer 0. A bump generated by crosstalk from the header of Layer 0 is observed, leading to potential difficulties in accurately binarizing the RF signal at the bump. This bump could generate address errors and destabilize focusing.

The recorded marks in Layer 0 also absorb the write laser directed at Layer 1 and the reflected light from Layer 1.

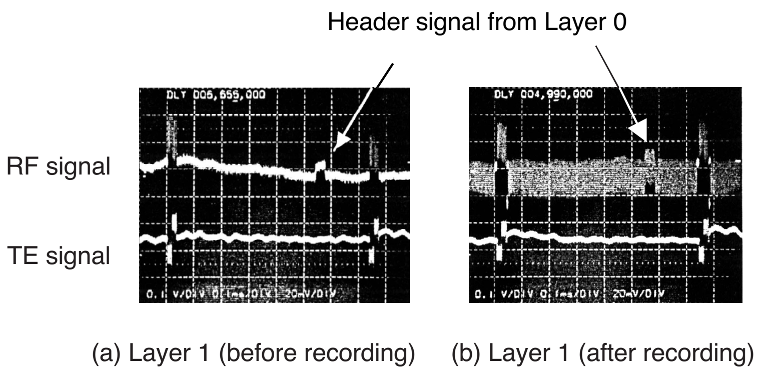


Fig. 2 RF signal of Layer 1 with crosstalk of header in Layer 0 (a) before recording and (b) after recording

It is concluded that the track structure should be as simple as possible to minimize any interference between the recording layers and the optical absorption differences between recorded areas and unrecorded areas. The recording layers also should be designed to have equivalent optical transmittance in both the amorphous state and the crystalline state.

2.2. ADDRESSING SCHEME FOR MULTI-LAYER FORMAT

For the next-generation blue-violet discs, several conceptual conditions should be set up to ensure extended forward compatibility.

(1) Applicability to all next-generation discs:
We must adopt a format with small overhead and random accessibility to enable a single format to be applied to ROM, WO, and RAM discs.

(2) Applicability to multi-layer recording:
The next-generation has to leave open the potential for expansion to over 50 GB, so it should remain suited to multi-layer recording. The track addressing format should be designed so as not to cause inter-layer disturbance.

(3) High reliability for reading Address and Data:
To permit random access, address readability during data writing should be reliable; also, the addressing signal should not generate any data errors when reading written data.

(4) Suitability for phase-change recording:
The format should include features such as SPS (Start Position Shift) recording.

(5) Random accessibility:
Sequential recording with precise linking and random recording are necessary for digital versatile usages.

2.3. STW (SAWTOOTH WOBBLE) FORMAT[7]

Fig. 3 shows the STW (SawTooth Wobble) format and Write Data structure. Each groove-like spiral track has a wobble signal. Data are written in the groove track. The wobble signals have up to now had a sinusoidal shape. STW consists of a new composition of a half cycle each of a sine wave and a sawtooth wave.

This gives STM both a steep slope and a gentle slope. The direction of the slopes varies according to Pattern "0" or Pattern "1." An address bit consists of 36 wobbles that are represented by repetitions of the same sawtooth pattern. The address bit can be decoded by majority decision within the repeated 36 wobbles. For one 16-kByte Data unit

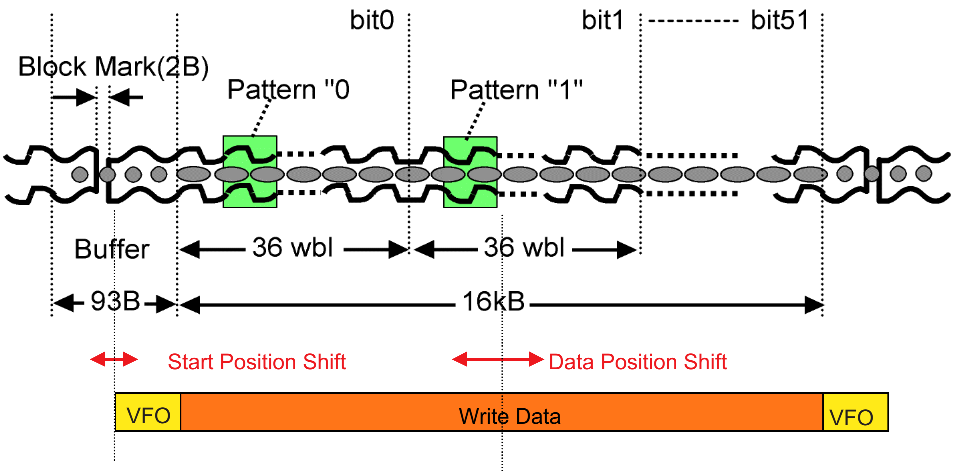


Fig. 3 Groove structure with STW (sawtooth wobble) and Write Data

block, 52 bits of information can be embossed as the Address Information and the Parity Code.

A Buffer area of 93 Bytes is allocated for every 16-kByte Data unit. In the Buffer area, the block mark is formed by a mirror part (land part) with an interval of 2 Bytes' length in a track. A block mark can be detected from the RF signal as a boundary of the Data unit. VFO (Variable Frequency Oscillator) patterns with a repetition of 4T marks are set at the top and the end of the Write Data. Write Data is overwritten in the Buffer area of 93 Bytes.

The VFO has PLL (Phase Locked Loop) and LPC (Laser Power Control) functions. The VFO is also used as a linking buffer, so it is possible to record Data units at random without data loss. The start position of the VFO and Write Data are shifted at random in every overwrite cycle to reduce the deterioration of the phase-change media[8].

If the ECC system of the DVD format is applied to the STW format, block size is (93 + 2418 x 8) Bytes for user data of (2048 x 8) Bytes. The format efficiency is estimated to be 84.3 %. The format efficiency of a DVD-ROM is 84.7 %.

Fig. 4 illustrates the physical dimensions of the STW. The groove is mastered by deep-UV laser beam with electro-optical deflector. The track pitch is 0.32 µm and the groove depth is λ/12. The track width is about 0.17 µm and wobble amplitude is from 10 to 20 nm. The period of one wobble is 155 channel bits when using the D8-15 codec[9].

Every wobble pattern is made from the combination of part of a sine wave and part of a square wave. Frequency response of the square part is about 10 times that of the sine wave part during mastering. The first order wave of the sawtooth is continuous even at the border of address bit "1" and bit "0."

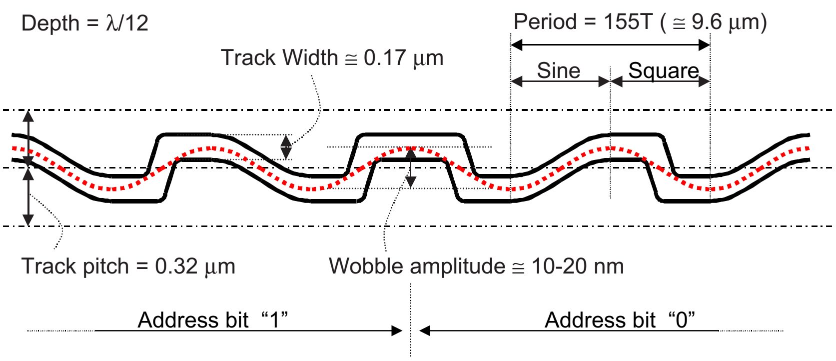


Fig. 4 Physical dimensions of sawtooth wobble

Fig. 5 shows an example of an STW signal, (a) pattern "0" and (b) pattern "1," under the conditions of wavelength 405 nm, NA 0.85, cover layer thickness 0.1 mm, and linear velocity 4.6 m/s.

Fig. 6 shows the results for the dual-layer rewritable phase-change disc with a distance between layers of 20 µm. Read

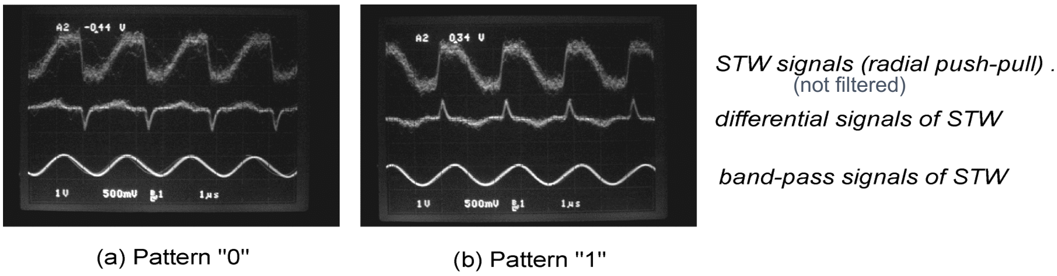


Fig. 5 Reproduced STW addressing signals (a) pattern "0" and (b) pattern "1"

power is 0.6 mW. Each layer of the dual-layer rewritable disc is readable to the same degree as on a single-layer rewritable disc. The radial push-pull signal is differentiated; hence, differential signals have polarized pulses corresponding to the rising slope or a falling slope of the sawtooth wave. The polarized pulses are level-compared and PID (Physical Information Data) is decoded.

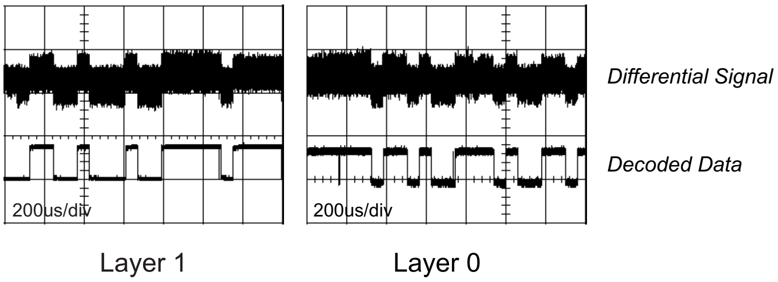


Fig. 6 STW signals of dual-layer disc

Table 2 shows track addressing methods and rating of applicability to multi-layer recording. CAPA (Complementary Allocated Pre-pit Address)[1] is applied to DVD-RAM, ADIP (Address Data in Pits) to +RW, and LPP (Land Pre-Pit) to DVD-R/RW.

The data track format should be groove recording to provide ROM compatibility. Wobble addressing is suitable for multi-layer recording when the reliability of address and data can be secured. To ensure user-friendly operation and readability by Read-only players, no "finalization" should be needed.

Table 2 Track addressing methods and rating of applicability to multi-layer recording

Item	CAPA	ADIP	LPP	STW
Interference between layers	3	2	2	1
Format overhead	3	2	1	1
ROM compatibility	2	1	1	1
Address read reliability	1	3	3	1
Data read reliability	1	1	2	1
Random accessibility	1	1	2	1
Suitability for phase-change recording	1	1	2	1
Necessity of finalization	No	Yes	Yes	Yes

1: Good, 2: Fair, 3: Poor

3. DUAL-LAYER 45 GB REWRITABLE DISC

The phase-change material of a rewritable dual-layer optical disc for a blue-violet laser should satisfy the following conditions:

(1) Large optical changes between amorphous and crystalline states at blue-violet wavelengths,

(2) High crystallization speed, even in a very thin film state,

(3) High optical transmittance: for example, more than 50 %, and

(4) Small interference between layers.

Yamada et al.[10] recently described how the conventional $Ge_2Sb_2Te_5$ composition is not suitable for a blue-violet laser and proposed a new phase-change material GeSn-Sb-Te (GSST), which is characterized by a richer GeTe content than in $Ge_2Sb_2Te_5$ and Sn(SnTe) substitution for a proportion of the Ge(GeTe) composition for Layer 0. The 6 nm-thick GeSbTe film with 10 % Sn shows a rapid crystallization time of less than 50 ns and high optical transmittance of 60 % can be obtained for the 6 nm thick GSST film.

Fig. 7 shows the film thickness dependence of the transmittance of GeSn-Sb-Te film and one of the eutectic compositions[11] as a reference when irradiated with 400 nm light.

In the case of the quaternary material GSST, equivalent transmittance can be obtained in both the amorphous and crystalline films, and a

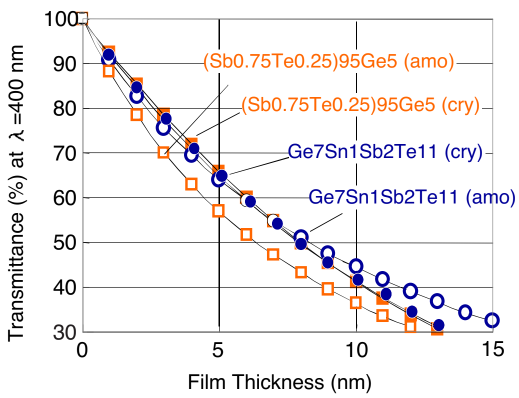


Fig. 7 Film thickness dependence of the transmittance of GeSn-Sb-Te film

high optical transmittance of 60 % can be achieved when the film thickness is 6 nm.

On the other hand, in the case of a eutectic composition, optical transmittance in the amorphous state is slightly lower than in the crystalline state, and the thickness should be under 5 nm to obtain a transmittance of 60 %.

Table 3 shows the disc parameters. Fig. 8 shows the layer structure of a thin cover layer dual-layer rewritable disc. Fig. 9 shows an eye pattern reproduced from the dual-layer 45 GB rewritable disc shown in Fig. 8 under the conditions listed in Table 3. Jitter was 10.8 % for Layer 0 and 10.3 % for Layer 1.

Table 3 Disc parameters

Capacity	45 GB
Wavelength/NA	405 nm/0.85
Track type	Groove (λ/12)
Track pitch	0.32 μm
Physical ID	STW
Bit density	0.129 μm
Modulation	D8-15
Min. mark size	0.206 μm
Read power	0.6 mW

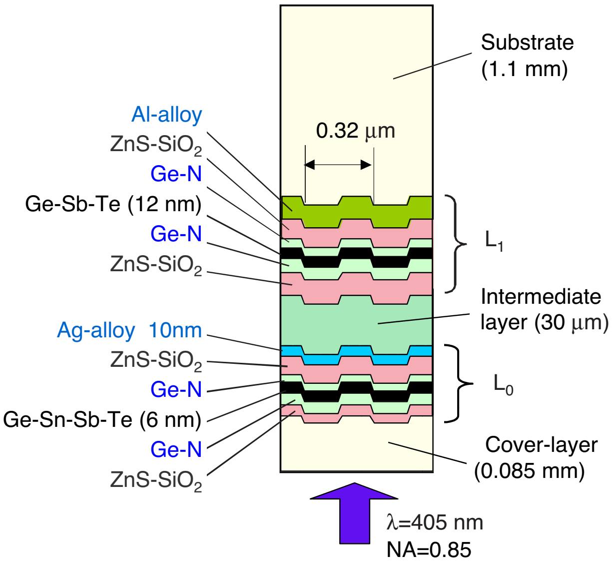
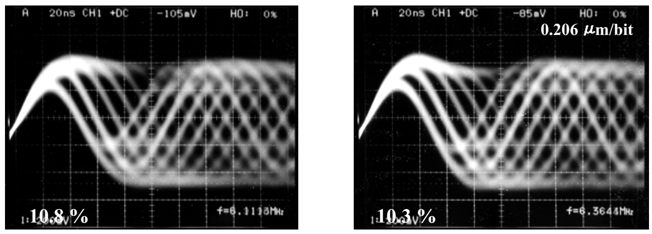


Fig. 8 Layer structure of thin cover layer rewritable disc



(a) Layer 0

(b) Layer 1

Fig. 9 Eye pattern from dual-layer 45 GB rewritable disc

4. EXPANSION TO QUADRUPLE-LAYER DISC

Kitaura et al.[12] proposed a quadruple-layer WO disc with 90 GB capacity.

Fig. 10 shows the quadruple-layer WO disc structure using palladium-doped tellurium suboxide film (Te-O-Pd)[13].
This film needs no initialization and recording is irreversible. Its amorphous, as-deposited film can be directly recorded, showing a phase-change into the crystalline state. This film shows the direction of reflection change of Low-to-High. To obtain high transmittance, the thickness of the Te-O-Pd film was set at 10 nm, and sandwiched by ZnS layers to obtain High-to-Low reflectivity and high reflectivity.

The thickness of the ZnS films was adjusted to obtain higher transmittance the closer they are to the

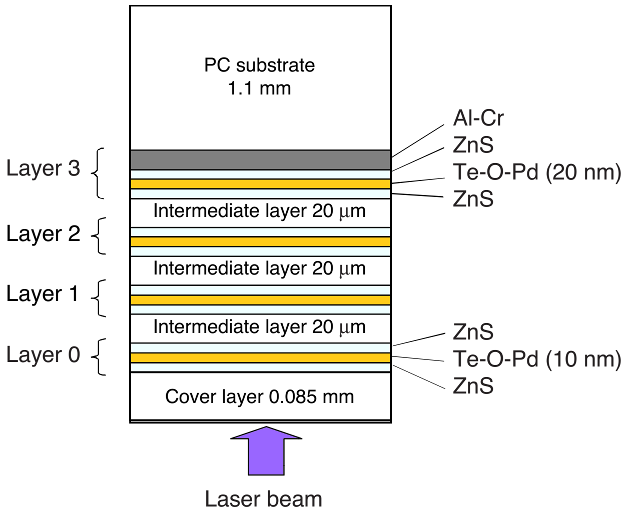


Fig. 10 Quadruple-layer structure of thin cover layer write-once disc

optical pickup: 78.8 %, 75.5 %, and 70 % for Layers 0, 1, and 2, respectively.

In Layer 3, a 20 nm thick Te-O-Pd film and Al-Cr alloy were used to obtain high reflectivity and high recording sensitivity with high absorption. The thickness of the intermediate layers was 20 µm, hence the distance from Layer 0 to Layer 3 becomes over 60 µm.

On the other hand, the tested optical pickup with an objective lens of NA 0.85 and a blue-violet laser of 405 nm wavelength could not compensate for spherical aberration over a range of 60 µm. Therefore, three types of quadruple-layer sample discs were prepared to evaluate the read and write characteristics under the conditions of track pitch 0.32 µm, mark size 0.206 µm, and velocity 5 m/s.

As shown in Fig. 11, the first disc was prepared for evaluation of Layer 0 and Layer 1 including Layer 2 and 3 as dummy layers. The second disc was for Layer 2 with dummy Layers 0, 1 and 3. The third disc was for Layer 3 with dummy Layers 0, 1, and 2. Each target layer was set within a range free from spherical aberration.

Fig. 12 shows the CNRs (Carrier to Noise Ratios) of the sample quadruple-layer discs. Each layer showed a CNR of more than 48 dB and Layer 3 showed the maximum value of more than 51 dB.

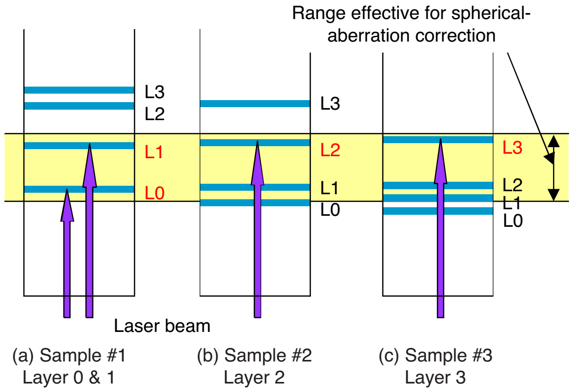


Fig. 11 Experimental sample discs for quadruple-layer WO disc

The recording sensitivity was from 7 mW to 12 mW.
Some write power variation may have occurred due to the absorption of the intermediate layers and the spherical aberration of the optical beam.

Although further work is needed to improve the manufacturing method and read/write system, the quadruple-layer WO disc has potential for expansion to a capacity of 90 GB with a wavelength of 405 nm and NA 0.85.

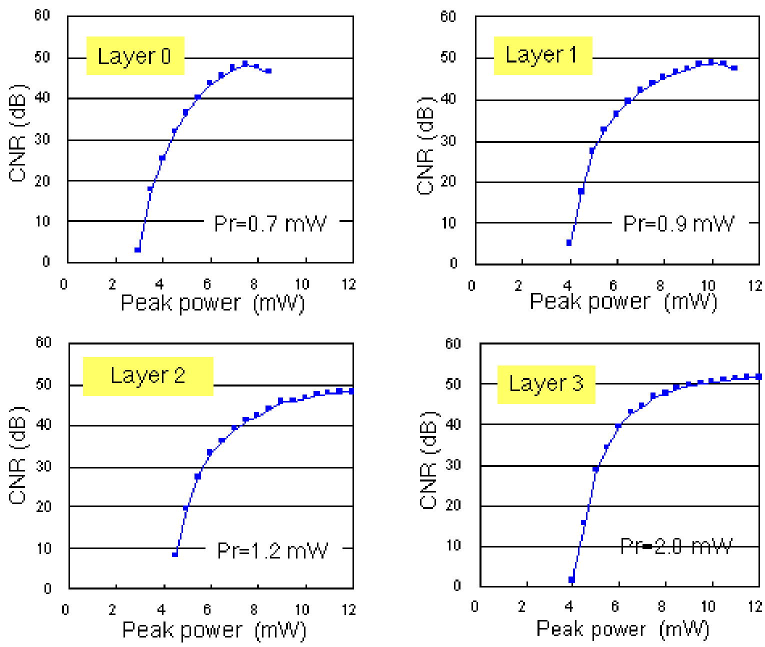


Fig. 12 CNRs of quadruple-layer write-once disc

5. CONCLUSIONS

The feasibility of multi-layer recording for the blue-violet next-generation was reviewed and physical formats applicable to multi-layer disc were discussed.

The STW format was proposed as a candidate for a single common format for ROM, WO, and RAM discs. It was implemented in a dual-layer rewritable disc and a quadruple-layer WO disc by combining a blue-violet laser, NA 0.85 lens, and thin cover layer.

A dual-layer rewritable disc and quadruple-layer WO disc have achieved the capacities of 45 GB and 90 GB, respectively. It should be stressed again that a multi-layer WO disc using Te-O-Pd film has the potential to achieve close to 100 GB due to its simple structure, low media cost, and robustness.

Regarding multi-layer recording for quadruple-layer or more discs, a key issue is how to compensate for the spherical aberration caused by optical path differences among the recording layers.

There are two approaches to the next-generation blue-violet disc shown in Table 4. One is a high-density approach using a blue-violet laser and a high NA objective lens with a thin cover layer; and the other is the DVD-compatible approach of directly applying a blue-violet laser to the DVD format.

From the user's viewpoint, it is important to make the system fully backward-compatible to CD and DVD so as not to lose access to materials recorded in these formats, and furthermore to increase the capacity to over 100 GB for extended recording of HDTV programs.

A third approach to expanding the capacity might be a jukebox. It could easily increase the system capacity by adding discs and finally break through existing limits on capacity.

Table 4 Two approaches to the next-generation discs

Approach	NA	Single-layer	Dual-layer	Quadruple-layer
DVD-compatible	0.65	15 GB	27 GB	54 GB
High-density	0.85	25 GB	45 GB	90 GB (WO)

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