Interlayer cross talk in dual-layer read-only optical disks

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Volumetric optical disks comprising multiple data layers have been proposed to multiply recording density. Owing to the presence of out-of-focus data layers, interlayer cross talk is induced in readout. An optical model was developed to study the readout process and the effect of interlayer cross talk on the readout of dual-layer read-only optical disks. Schemes to improve the readout characteristics by suppression of the interlayer cross talk were proposed. Experiments that agreed well with the simulation resulted. © 1999 Optical Society of America

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1. Introduction

Volumetric optical storage multiplies the recording density by incorporating plural data layers as recording media, with the data recorded on each layer of the multilayer structure.[1–3] The concept and the attractive attributes of volumetric optical storage were widely accepted with the commercialization of DVD[4] (digital versatile disk). Significant efforts were made to develop volumetric optical disks through suitable modification of the reflectance of thin-film layers, such as magneto-optical, phase-change, or dye-based media.[3,5–10] Novel schemes were proposed for volumetric optical storage, for example, the application of multiple-wavelength multiplexing[6,11] or liquid-crystal–based media[12] to multilayer optical disks.

If the readout performance of volumetric optical disks is to be improved, the interlayer cross talk,[11,13] which is unique in readout from a multilayer optical disk, requires systematic exploration. The present study was devoted mainly to examining the effect of interlayer cross talk by a theoretical approach, the feasibility of which was then justified by experiments. An optical model was developed to simulate the readout from dual-layer read-only optical disks. The dependence of interlayer cross talk on the parameters of the disk structure and the optical head was investigated. More reliable readout performance was achieved by suppression of interlayer cross talk through proper design of the disk structure and appropriate configuration of the detection channel. The readout characteristics of multilayer optical disks, such as the rf readout signal, the power spectrum, and the readout modulation, were derived by readout modeling; experiments were performed to correlate with the model.

2. Readout Modeling of Dual-Layer Optical Disks

To explore the effect of interlayer cross talk on the readout signal, we modeled a dual-layer read-only optical disk to examine the roles of the focused and the out-of-focus data layer in the readout process. The dual-layer optical disk[7,8] in the model was composed of two polycarbonate substrates, one coated with a semireflective[3] and one with a totally reflective Al layer, as shown in Fig. 1. The data layers of the optical disk were separated from each other by an air spacer[3,5–6] of 40 μm in thickness to reduce the interlayer interference. A laser beam of wavelength $\lambda = 780$ nm was focused by an objective lens of 0.45 numerical aperture (NA) and irradiated onto the dual-layer optical disk, which was spinning at a linear speed of $\nu = 1.4$ m/s for readout.

A. Simulation of Interlayer Cross Talk

The rf readout signal and the interlayer cross talk could be derived from the diffraction-limited and the enlarged laser spots on the focused and the out-of-focus data layers, respectively, of the dual-layer optical disks. For a dual-layer optical disk there are two readout modes: mode 1 is defined to read the totally reflective layer; mode 2 is defined to read the semireflective layer. In mode 1 the semireflective layer, which falls outside the depth of focus of the pickup head, reflects back a portion of the readout

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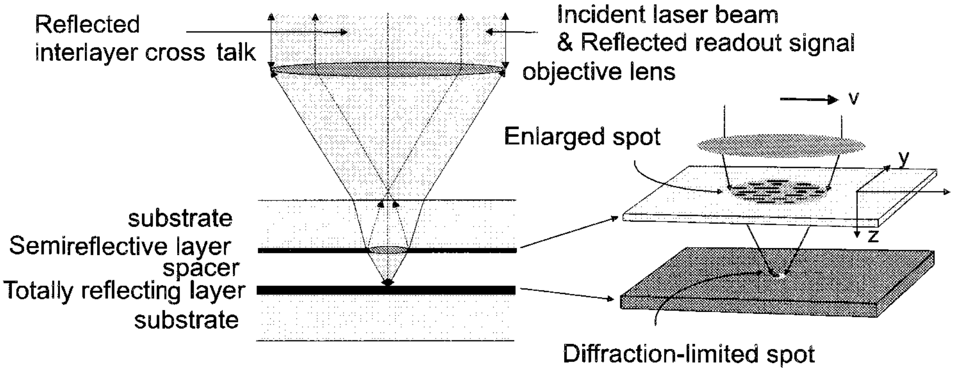


Fig. 1. Laser beam focuses to read data on the totally reflective layer of a dual-layer read-only optical disk. Multiple data marks on the out-of-focus layer are irradiated by the enlarged spot and result in interlayer cross talk.

radiation, which consequently couples into the readout signal and induces interlayer cross talk, as shown in Fig. 1. On the semireflective layer the laser light is spread out, so that an enlarged laser spot is imaged. It is the laser beam reflected from the enlarged spot that intrudes into the readout channel and results in interlayer cross talk. With the assumption that the FWHM (full width at half-maximum) of the diffraction-limited spot was $0.6\lambda/\mathrm{NA}$,[14] the $1/e$ radius of the enlarged spot, with the electric-field amplitude reduced to $1/e$ of the value at beam center, was found to be $\sim 19.96\ \mu\mathrm{m}$ by application of the *ABCD* law.[15] Correspondingly, there were ~200 data marks simultaneously illuminated by the spot.

Because of the splitting effect of the semireflective layer,[5] the magnitudes of the rf signal $S(t)$ and the interlayer cross talk $N(t)$ are governed chiefly by the amount of optical energy allocated to the totally reflective and the semireflective data layers, respectively. The reflectivity (R), the transmissivity (T), and the absorption coefficient (A) of individual data layers are derived as[16]

$$R = \left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)\left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)^*,$$

$$T = \frac{4\eta_0\,\mathrm{Re}(\eta_m)}{(\eta_0 B + C)(\eta_0 B + C)^*},$$

$$A = \frac{4\eta_0\,\mathrm{Re}(BC^* - \eta_m)}{(\eta_0 B + C)(\eta_0 B + C)^*}, \qquad (1)$$

where η_0 and η_m denote the optical admittances[16] of the incident and the exit media, respectively, and the parameters B and C denote the matrix elements of the product of all optical matrices[16] identifying the corresponding thin films. The interference of the laser beam propagating between the data layers is taken into consideration in the model so that the optical energy accumulated on the out-of-focus data layer that results in interlayer cross talk is derived.[17]

The interlayer cross talk, denoted $N(t)$, is derived by taking the convolution[13,17] of the enlarged spot profile and the reflectivity distribution of the out-of-focus data surface:

$$N(t) = \iint f(x(t), y)^* h(X(t) - x(t), y)\,\mathrm{d}x\mathrm{d}y, \qquad (2)$$

where $h(x, y)$ denotes the optical energy accumulated on the out-of-focus layer. The spatial function $f(x, y)$, which comprises a numerically simulated, semi-infinite matrix of phase marks in random order, defines the reflectivity distribution of the out-of-focus data surface. Through the average effect of ~200 simultaneously irradiated data marks, the induced interlayer cross talk approximates dc noise. The interlayer cross talk is high-frequency modulated in accordance with the varying count of data marks encompassed by the spot scanning on the out-of-focus layer, as shown in Fig. 2.

B. Dependence of Interlayer Cross Talk on the Focusing Lens and the Spacer Layer

The objective lens of higher NA will induce interlayer cross talk with a higher dc content. The focusing cone angle of the incident beam, as shown in Fig. 1, is expanded if a focusing lens of higher NA is employed.

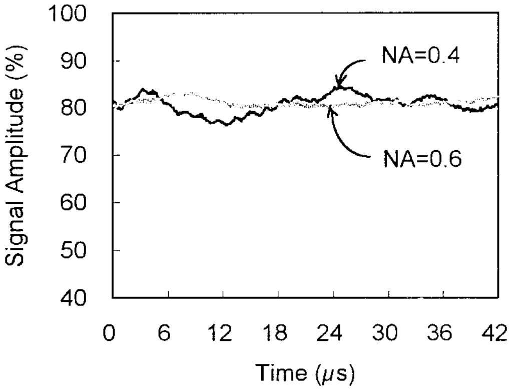


Fig. 2. Interlayer cross talk simulated from the out-of-focus layer when the NA of the objective lens is 0.4 or 0.6. The x axis denotes the scanning time of the laser beam. The minimum signal amplitude (derived from a mark region) is set to be 0; the maximum amplitude (derived outside the mark region) is set to be 100%.

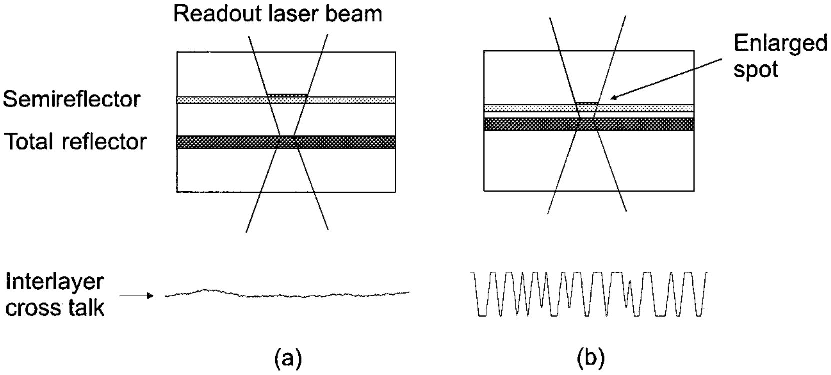


Fig. 3. Interlayer cross talk induced in dual-layer optical disks when the spacer thickness is (a) 40 μm, and (b) 2 μm (approximately the depth of focus).

Therefore the number of data marks illuminated by the enlarged spot is increased, which smoothes the fluctuation of the induced interlayer cross talk, as shown by the curve for the 0.6 NA in Fig. 2.

The thinner the spacer layer is, the smaller the laser spot formed on the out-of-focus data layer, and thus the more detrimental the interlayer cross talk. If the thickness of the spacer is reduced to have the out-of-focus layer fall within the depth of focus of the beam, as shown in Fig. 3(b), the enlarged spot will be reduced to the diffraction-limited size, which induces interlayer cross talk approximating the rf signal derived from the focused laser. The interlayer cross talk then interferes severely with the rf signal and significantly affects the accuracy of signal detection. Hence a spacer of adequate thickness is essential in configuring a volumetric optical disk to suppress interlayer cross talk.

C. Effect of Interlayer Cross Talk on the Signal-to-Noise Ratio

For a dual-layer optical disk with a spacer significantly thicker than the depth-of-focus of the beam, the interlayer cross talk approximates a dc component, as shown in Fig. 3(a). In this case the noise level of the readout spectrum will not be affected by the intrusion of interlayer cross talk. Because the out-of-focus layer reflects a portion of the laser energy to induce interlayer cross talk, the rf signal derived from the focused layer is attenuated, and the peak of the signal band in the readout spectrum is suppressed. Thus the signal-to-noise ratio obtained from a dual-layer optical disk is reduced compared with a conventional single-layer optical disk.

If the spacer thickness is reduced to some micrometers (approaching the depth of focus), as shown in Fig. 3(b), the enlarged spot induces interlayer cross talk, which approximates the rf signal derived from the focused layer. The interlayer cross talk raises the noise level to near that of the signal band; consequently, the increased noise level, along with the suppressed signal band, results in a lower readout signal-to-noise ratio.

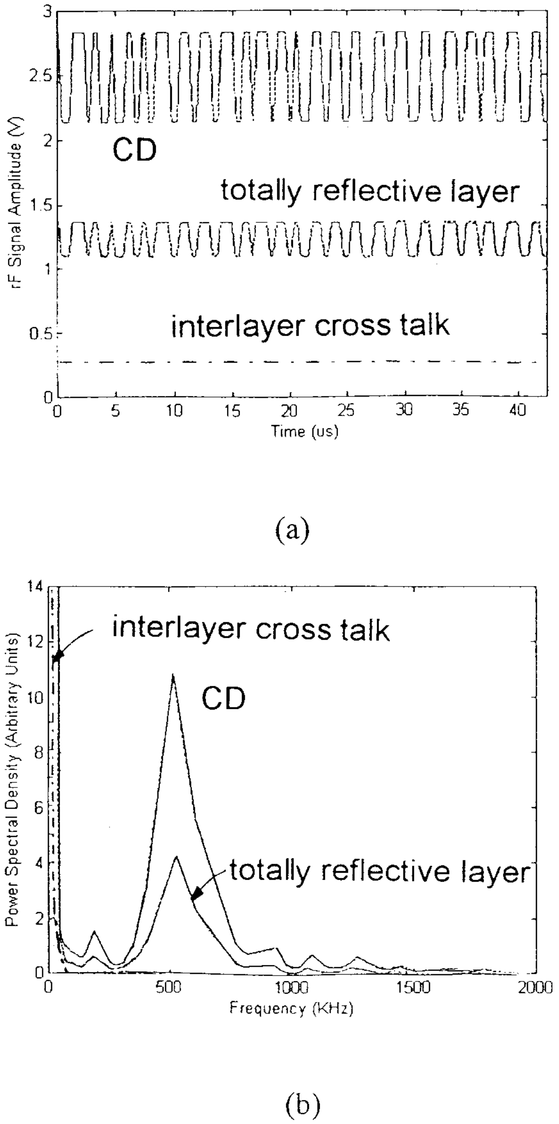
3. Effect of Interlayer Cross Talk

A. Readout on the Totally Reflective Layer

Interlayer cross talk attenuates the rf readout signal and degrades the readout contrast. To analyze the effect of interlayer cross talk, we derived the degraded rf readout signal $S(t)$ by convolution of the energy profile of the diffraction-limited spot and the reflectivity distribution of the random marks on the focused data layer. In the simulation of the rf readout signal, the detection channel (from the objective lens to the detector) was characterized by a conventional CD signal measured from an optical disk testing system. A CD-ROM drive was modified to act as the testing system to derive the rf readout signal from dual-layer optical disks.[18] The rf power spectrum and readout modulation of the dual-layer optical disk could each then be derived from the readout electronics.

The rf readout signal derived from the totally reflective layer of a dual-layer optical disk is suppressed in magnitude owing to the optical masking of the reflective–absorptive semireflective film. The rf signal derived from the totally reflective layer of a dual-layer optical disk with a 25-Å-thick semireflective layer, for example, was simulated by means of readout modeling, as shown in Fig. 4(a), to be compared with the measured result [shown in Fig. 5(a)] in signal magnitude and dynamic range. The simulated wave pattern was derived by modulation of reflected light as the read beam scanned over the embossed data marks and the intermediate unwritten area. The dynamic range of a single-layer CD signal was $(V_{\mathrm{low}}, V_{\mathrm{high}}) \cong (2.2, 2.8\ \mathrm{V})$, and that of the dual-layer optical disk was $(V_{\mathrm{low}}, V_{\mathrm{high}}) \cong (1.1, 1.3\ \mathrm{V})$ in Fig. 4(a) or 5(a), considerably attenuated owing to the existence of the semireflective layer. A similar agreement between the simulation and the experiments holds in the cases of dual-layer optical disks with other thicknesses of semireflective layers.

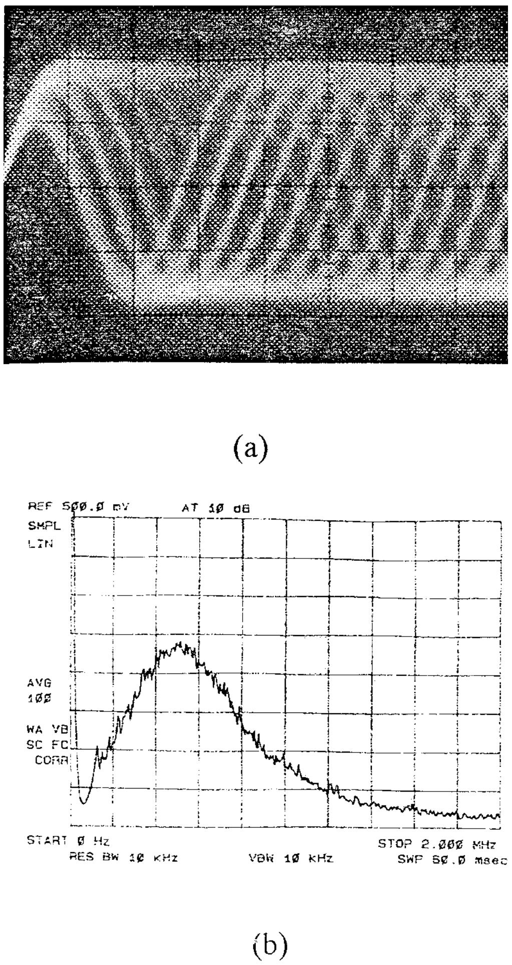
The dc essence of interlayer cross talk is more clearly revealed in the readout spectrum, which is provided by the fast Fourier transform of the simulated rf readout signal. The amplitude of the power spectrum derived



(a)

(b)

Figs. 4. (a) Simulated rf signal and (b) power spectrum in reading a CD and a totally reflective layer of a dual-layer ROM disk with a 25-Å-thick semireflector, where the dotted–dashed curves denote the interlayer cross talk. The spacer thickness is 40 μm.



(a)

(b)

Figs. 5. (a) rf signal (eye pattern) and (b) rf power spectrum measured in reading the totally reflective layer of the dual-layer optical disk with a 25-Å-thick semireflector. In (a) the dc offset is 1.2 V; the horizontal and the vertical scales are 0.5 μs/division and 50 mV/division, respectively.

from the dual-layer optical disk (~4.2 units) is suppressed compared with that of a single-layer CD signal (~10.8 units), as is shown in Fig. 4(b). The dc nature of the interlayer cross talk is shown in the dotted–dashed spectrum of Fig. 4(b), where the high-frequency components of the interlayer cross talk are nearly unobservable. More computation points in the time scale would smooth the spectrum further to resemble the measured one, as shown in Fig. 5(b), but at the expense of computation time.

Besides the rf signal and the power spectrum, the readout contrast is degraded in readout because of the intervention of interlayer cross talk in the rf readout signal. The readout modulation is defined by the ratio of ac to dc components of the rf signal:

$$\text{readout modulation} \equiv \frac{\mathrm{AC}}{\mathrm{DC}} \times 100\%, \qquad (3)$$

where AC and DC denote the ac and dc components of the rf readout signal, respectively. DC, AC, and the readout modulation simulated from dual-layer optical disks are shown in Fig. 6 as functions of semire-

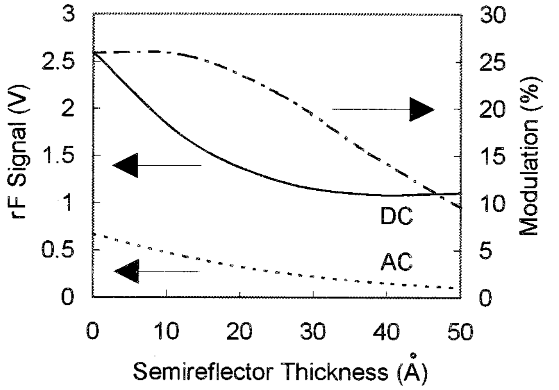


Fig. 6. dc and ac components and readout modulation of the rf signal simulated from the totally reflective layer of the dual-layer optical disk. The spacer thickness is 40 μm.

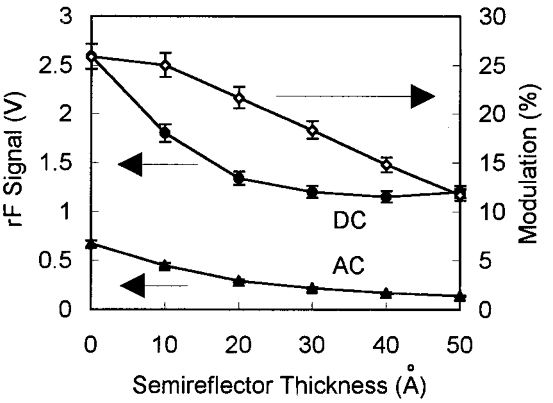


Fig. 7. dc and ac components and readout modulation of the rf signal measured from the totally reflective layer of the dual-layer optical disk.

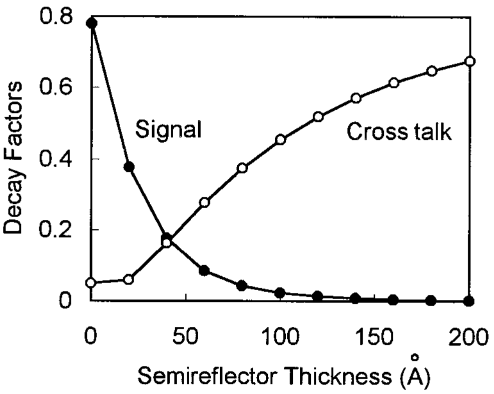


Fig. 8. Decay factors of the rf signal and the interlayer cross talk in read mode 1 as a function of semireflector thickness.

flector thickness. In the case of negligible interlayer cross talk, both AC and DC are attenuated by the same proportion in traversing the semireflective layer; however, a portion of the dc content reflected or absorbed by the semireflector is compensated by the intruding dc-based interlayer cross talk. Therefore the ac signal of the resulting rf signal is more attenuated than the dc level, so the readout modulation is degraded by the interlayer cross talk, as shown in Fig. 6. The experimental result, in accordance with the simulated one in Fig. 6, is depicted in Fig. 7 for comparison. The experimental result agrees well with the simulated results. The thicker the semireflective layer is, the more serious the degradation of the readout modulation.

B. Readout on the Semireflective Layer

Without the obstruction of the out-of-focus data layer, it is more direct and easier to read data on the semireflective layer than on the totally reflective layer. Induced from the totally reflective layer and attenuated in traversing the semireflective layer,[13] less serious interlayer cross talk results in read mode 2. As in read mode 1, the readout modulation derived in mode 2 is degraded by the interlayer cross talk induced from the totally reflective layer.

4. Suppression of Interlayer Cross Talk

For improving the readout performance of a multilayer optical disk, a number of schemes could be applied to suppress the effect of interlayer cross talk: suitably designing the disk structure, screening the return beam carrying the interlayer cross talk, or filtering the interlayer cross talk through detection circuitry. The reflectivities of the data layers are preferably adjusted to match so that a balanced amount of optical energy returns to the objective lens from each data layer.[3] A dual-layer read-only optical disk with balanced readout was designed by means of readout modeling. In read mode 1, the rf signal derived from the totally reflective layer was attenuated by a decay factor of $\sim T_1 \times R_2 \times T_1$ to a first-order approximation, with T_1 the transmissivity of the semireflective layer and R_2 the reflectivity of the totally reflective layer; the interlayer cross talk induced from the semireflective layer was attenuated by a decay factor of $\sim R_1$, the reflectivity of the semireflective layer. The two decay factors are depicted in Fig. 8 as functions of the semireflector thickness. For read mode 2, the curve with filled circles denotes the decay factor of the rf readout signal ($\sim R_1$) in contrast to read mode 1, and the curve with open circles denotes that of the interlayer crosstalk ($\sim T_1 \times R_2 \times T_1$). As is shown in Fig. 8, the magnitudes of the rf signals derived from the two data layers of a dual-layer optical disk with a 40-Å-thick semireflector are almost the same; so the system can perform without extra signal-balancing circuitry in the readout channel.

By isolating the read beams carrying the rf signal and the interlayer cross talk, one can suppress the interlayer cross talk optically or electronically. In the return path of the laser beam there are two focal planes, corresponding to the two data surfaces of the dual-layer optical disk. With an iris correctly positioned at the focal plane corresponding to the focused data layer to pass the beam carrying the desired rf signal, most of the light that carries interlayer cross talk is blocked and fails to impinge upon the optical detector. Since the interlayer cross talk is dc based, the residual of the interlayer cross talk that leaks through the iris can subsequently be filtered by high-pass filtering circuitry to pass the desired rf signal for readout.

5. Conclusion

A dual-layer optical disk was modeled to allow us to study the effect of interlayer cross talk on readout. The interlayer cross talk, which is induced by an enlarged spot radiated onto the out-of-focus layer, is a high-frequency, broadband noise. The out-of-focus data layer obstructs the incident beam and attenuates the rf readout signal; the intrusion of interlayer cross talk in the rf readout signal degrades the readout contrast. Balanced readout is achievable in a properly designed disk structure; through appropriate construction of optics and electronics, interlayer cross talk can be significantly suppressed. The agreement between the simulation and the experiment allows the readout analysis to be extended to more advanced volumetric optical disks.

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References

1. P. G. Wohimut and F. D. Neu, "Three dimensional electro-optical retrieval system," U.S. patent 3,946,367 (3 March 1976).
2. J. R. Wullert and P. J. Delfyett, "Multiwavelength, multilevel optical storage using dielectric mirrors," IEEE Photonics Technol. Lett. **6,** 1133–1135 (1994).
3. P. L. Holster and J. M. Wittkimper, "Multilayer information disc," U.S. patent 4,450,553 (22 May 1984).
4. T. Kashiwagi, "Dual layer disk overview," in *Joint International Symposium on Optical Memory and Optical Data Storage*, Vol. 12 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), pp. 11–13.
5. W. I. Imaino, H. J. Rosen, K. A. Rubin, and W. W.-C. Tang, "Optical data storage system with multiple write-once phase-change recording layers," U.S. patent 5,555,537 (10 September 1996).
6. H. J. Rosen, K. A. Rubin, and W. W.-C. Tang, "Optical disk data storage system with multiple write-once dye-based data layers," U.S. patent 5,627,817 (6 May 1997).
7. K. Nishiuchi, H. Kitaura, N. Yamada, and N. Akahira, "Write-once type dual-layer optical disk using Te-O-Pd phase-change films," in *Digest for Joint Conference of Magneto-Optical Recording International Symposium/International Symposium on Optical Memory '97* (Business Center for Academic Societies Japan, Tokyo, Japan, 1997), pp. 56–57.
8. J. M. Bruneau, B. Bechevet, and C. Germain, "Optical design for a double DVD-RAM phase-change disc," in *Digest for Joint Conference of Magneto-Optical Recording/International Symposium on Optical Memory '97* (Business Center for Academic Societies Japan, Tokyo, Japan, 1997), pp. 58–59.
9. H. J. Rosen, K. A. Rubin, W. W. C. Tang, and W. Imaino, "Multilayer optical recording (MORE)," in *Optical Data Storage '95*, G. R. Knight, H. Ooki, and Y.-S. Tyan, eds., Proc. SPIE **2514,** 14–19 (1995).
10. K. A. Rubin, H. J. Rosen, T. McDaniel, and W. W.-C. Tang, "Volumetric magneto-optic storage on multiple recording surfaces," in *Joint International Symposium on Optical Memory and Optical Data Storage*, Vol. 12 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), p. 10.
11. S. Homan and A. E. Willner, "High-capacity optical storage using multiple wavelengths, multiple layers and volume holograms," Electron. Lett. **31,** 621–623 (1995).
12. W. Schlichting, S. Faris, B. Fan, J. Haag, Z. Lu, L. Li, T. Milster, and H. Luo, "Recording and read-out of a cholesteric liquid crystal based multilayer disk," in *Joint International Symposium on Optical Memory and Optical Data Storage*, Vol. 12 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), pp. 230–232.
13. K. A. Rubin, H. J. Rosen, W. C. Tang, W. Imaino, and T. C. Strand, "Multilevel volumetric optical storage," in *1994 Topical Meeting on Optical Data Storage*, D. K. Campbell, M. Chen, and K. Ogawa, eds. Proc. SPIE **2338,** 247–253 (1994).
14. A. B. Marchant, *Optical Recording: a Technical Overview* (Addison-Wesley, Reading, Mass., 1990), Chap. 5, p. 106.
15. A. Yariv, *Optical Electronics* (Saunders College Publishing, Philadelphia, 1991), Chap. 2, p. 50.
16. H. A. Macleod, *Thin-Film Optical Filters* (McGraw-Hill, New York, 1990), Chap. 2, pp. 15, 32–39.
17. E. Hecht, *Optics* (Addison-Wesley, Reading, Mass., 1987), Chap. 2, p. 22; Chap. 4, p. 487.
18. W. I. Imaino, H. J. Rosen, K. A. Rubin, T. C. Strand, and M. E. Best, "Extending the compact disk format to high capacity for video applications," in *1994 Topical Meeting on Optical Data Storage*, D. K. Campbell, M. Chen, and K. Ogawa, eds. Proc. SPIE **2338,** 254–259 (1994).