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Research on Optical Recording with Short-Wavelength Light Source

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Abstract:

To develop a third-generation large-capacity storage device, basic research was conducted on short-wavelength optical recording. An argon ion laser and a semiconductor laser-pumped YAG-SHG laser were studied as short-wavelength light sources for optical recording. An optical disk evaluating apparatus using an argon ion laser as the light source was trially manufactured, and basic data were accumulated for future high-density storage devices. The write and read characteristics of bismuth-substituted garnet as a short-wavelength optical recording medium were measured with the optical disk evaluating apparatus. This primitive-stage experiment confirmed the write and read functions of the optical recording medium and yielded results suggesting the future possibility of short-wavelength optical recording.

1. Introduction

Since 1986 when it was founded by its former name of the Electronics Division, Nippon Steel's Electronics & Information Systems Divisions Group has carried out basic research on optoelectronics jointly with the Company's research laboratories as part of a project in pursuit of possible new businesses. Computers and peripheral devices were the target area of the electronics and communication business, and optical information processing was emphasized in optoelectronic research. When the research laboratories were reorganized in 1989, the Electronics Research Laboratories was inaugurated, completing a system for carrying out the research and development of future technology in the electronics and communications markets.

In 1990, the Electronics & Information Systems Divisions Group commissioned the Electronics Research Laboratories and the Advanced Materials & Technology Research Laboratories to jointly perform basic research on optical storage devices for the purpose of searching for basic technology in the future information equipment business. This article describes technical trends about optical storage devices, and presents the objectives and present situation of research on optical storage devices at Nippon Steel.

2. Optical Storage Devices

2.1 History of optical storage devices

The storage device is an indispensable element of the computer. Various storage devices are used in specific applications. Magnetic storage devices, such as magnetic disks and magnetic tapes, have been used chiefly as secondary storage devices for programs and data. In the optical storage device, a laser beam is focused on a spot on a recording medium, and the irradiated spot physically or chemically changes to record data. During the read pass, a weak read laser beam is focused on the spot, and the resultant change in the reflectivity or transmissivity of the spot is read as data. This is the recording principle of the optical storage device.

The size of record bits that is dependent on the spot diameter of the laser beam focused by lens in the optical storage device

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is by far smaller than that of record bits in the magnetic storage device. The optical storage device has therefore been looked upon as an ideal large-capacity storage device. The concept of optical storage device already appeared in the late 1960s when the laser was invented. Specifically, the compact disk (CD) was commercialized for recording music in 1983, and the video disk (VD) was marketed for recording animation in 1981. As is well known, the CD and VD have formed huge markets of their own ever since.

Both the compact disk and video disk players can only read the data recorded in the disk, which is reproduced from the original by the stamping mathod. Write once read many (WORM) optical storage devices were developed in 1981 as secondary storage devices for computers and are now adopted as external storage devices for large-capacity files like archival files.

Various types of rewritable optical storage devices have been studied. In 1987, a 130-mm diameter disk utilizing the magneto-optical effect was announced as a full-fledged external storage device.

Optical storage devices feature the following:

(1) The storage capacity is large (650 MB on two sides of the 130-mm disk)

(2) Disks can be changed, which produces the following derivative features:
- The disk change provides an unlimited storage capacity.
- The user can use the removable disk to bring about his or her own system software, including the operating system, and can enjoy his or her own working environment in any place.
- Disks can be removed and stored for data security.

(3) Disks can store records for 10 years or longer, by far longer than magnetic tapes used in similar applications.

In this way, optical storage devices have features that are different from those of conventional magnetic storage devices. Optical storage devices, mainly of the rewritable type, have begun to be used for high-capacity archival files.

2.2 Technical trends

Rewritable optical storage devices are mainly of the magneto-optical type. The principle of magneto-optical recording is as shown in **Fig. 1**. A laser beam is focused on a spot on a disk while an external magnetic field is applied perpendicular to the disk surface. The spot is magnetized in the same direction as the external magnetic field, and a data is written at the spot in the direction of magnetization. During the read pass, the data written at the spot is read back by utilizing the Kerr effect that the polarization direction of the laser light reflected from the spot on the disk is different from the direction of magnetization. Various types of magneto-optical recording media are reported, among which TbFeCo is now predominant.

Since the recording media of optical storage devices are removable, it is important to ensure compatibility between different makes of optical disks and between different makes of optical storage devices. The International Organization for Standardization (ISO) established an international standard for 130-mm rewritable optical disk cartridges in 1991, and for 90-mm rewritable optical disk cartridges in 1992. This standardization of optical disk specifications is expanding the optical storage device market.

Magnetic disk devices, today's principal secondary storage devices, are rapidly decreasing in size and price and increasing in capacity. Optical storage devices are gradually coming to be used in such special applications as large-capacity files and archival files, but their use in large quantities as secondary storage devices of computers is yet to be seen. This is because 1) optical storage devices are lower in access speed and transfer speed than magnetic storage devices, and 2) these are few established applications as yet where large-capacity removable recording media

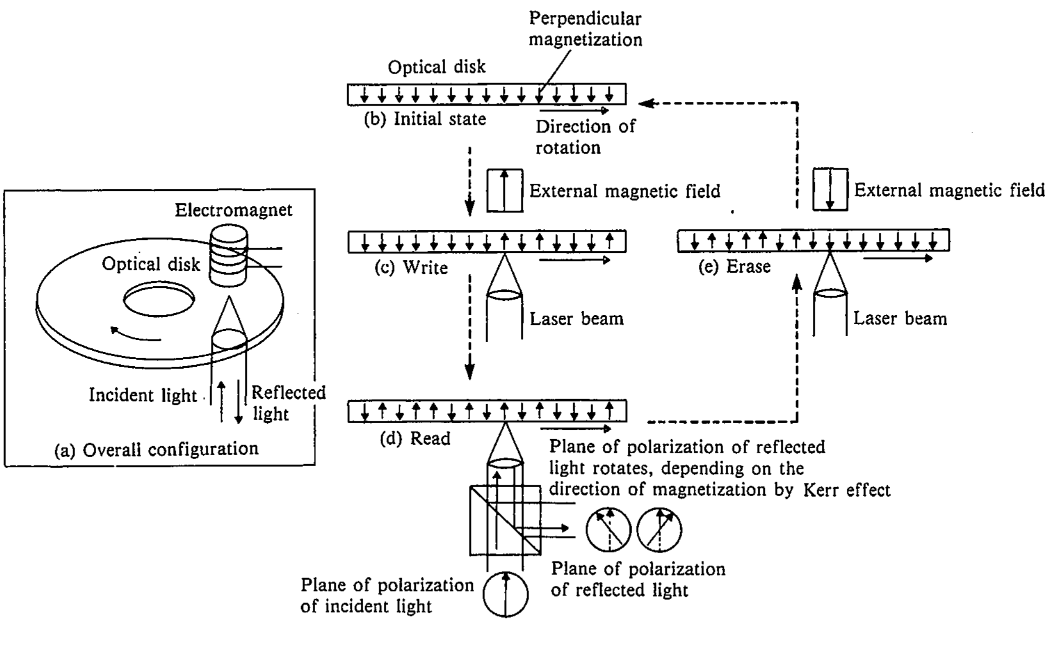

Fig. 1 Principle of magneto-optical recording

are necessary[1]. Work has started on the standardization of next-generation optical disks with the object of improving the functionality and expanding the application field of optical storage devices. At the same time, technical studies have been initiated toward larger capacities in future optical storage devices.

2.3 Capacity increasing technology

Described here technologies to increase the recording density as a means of enlarging the storage capacity. Several methods can be considered for increasing the storage capacity of optical disks. Some of the methods are summarized in **Table 1**. Combined use of several methods is expected to increase the storage capacity by more than 100 times[2].

Of the methods listed in **Table 1**, the most basic is the one that uses a laser beam of shorter wavelength. The spot diameter of the laser beam focused by lens is proportional to the wavelength of the laser beam. If the wavelength of the laser beam is 1/2, for example, the spot diameter can be halved, and the recording density per unit area can be quadrupled.

Short-wavelength lasers are under development with the aim of increasing the storage capacity of optical disks. They are now expected to appear on the market within a few years. The standardization of next-generation optical disks aims first at a second generation having the storage capacity doubled or tripled without changing the present laser wavelength but by signal processing and other techniques. The third generation will have the capacity increased five to ten times through the use of short-wavelength lasers. Second-generation and third-generation optical disks and storage devices are expected to appear on the market in this year (1993) and four to six years later, respectively.

Table 1 Methods for increasing capacity of optical disks

Classification	Method	Effect
Signal processing	Mark width recording	×1.5 maximum
	Mark length recording	×1.5-2
Reduction in focused spot diameter	Use of short-wavelength laser	630 nm ×1.5 530 nm ×2.1 420 nm ×3.3
	Use of high-NA*1 objective lens	×1.2-1.5
Effective utilization of disk surface	Land groove recording	×2 maximum
Superresolution	Magnetically induced superresolution (MRS)	×2-4
	Optical system	×1.5 maximum

*1 NA: Numerical aperture

3. Apparatus for Evaluating Optical Disks with Short-Wavelength Light Source

As described above, optical recording with a short-wavelength light source is an important technology to increase the capacity of third-generation optical storage devices to appear four to six years later. To achieve optical recording with a short-wavelength light source, it is necessary to acquire a practical short-wavelength light source, to develop a storage device capable of using the short-wavelength light source, and to develop an appropriate short-wavelength optical recording medium. To gather basic data on the light source and recording medium required for a third-generation optical storage device with short-wavelength optical recording, the authors fabricated an apparatus for evaluating magneto-optical disks using a short-wavelength light source and started the basic experimentation of short-wavelength magneto-optical recording.

3.1 Light source

3.1.1 Short-wavelength light source for optical storage device

Table 2 lists the conditions required of light sources for optical storage devices and the specifications of possible light sources. Short-wavelength lasers considered to be at practical levels for optical storage devices are: 1) argon ion laser; 2) semiconductor laser-pumped YAG-SHG laser; 3) direct SHG of semiconductor laser; and 4) II-VI compound short-wavelength semiconductor laser. While the wavelength of the AlGaAs semiconductor laser widely used as light source for today's magneto-optical storage devices is 780 nm in the infrared region, the above four types of lasers fall in the blue-to-green region of the spectrum. The AlGaAs semiconductor laser practically satisfies the optical recording requirements except that its wavelength is infrared. It cannot be said, however, that all the present short-wavelength lasers fully meet the requirements of optical storage devices.

Table 2 Conditions required of light sources for magneto-optical storage devices and possible light sources

Condition		Present light source		Candidate for light source of shart-wave length recording							
Item	Range	Semiconductor laser (AlGaAs)		Argon ion laser		Semiconductor laser-pumped YAG-SHG laser		Semiconductor laser-direct SHG laser		II-VI compound short-wavelength semiconductor laser	
Wavelength	As short as possible	780-840nm	△	488nm 515nm	○	530nm	○	400-600nm	◎	450-550 nm (CdZnSe)	○
Optical output power	≥ 30 mW	≥ 50 mW	◎	≥ 50 mW (air cooled)	◎	≥ 30 mW	◎	≤ 10 mW Future improvement expected	△	≤ Several milliwatts Future improvement expected	×
Response time	≤ 10 ns	Several nanoseconds	◎	External modulator required	×	External modulator required	×	Comparable to AlGaAs semiconductor laser	◎	Several nanoseconds expected	◎
Noise (RIN*1)	$\leq 10^{-14}$	Achieved by high-frequency superimposition	○	Almost achieved	○	Room for improvement	△	Comparable to AlGaAs semiconductor laser	○	Comparable to AlGaAs semiconductor laser	?
Lifetime	≥ 30,000 h	≥ 10,000 h at room temperature	○	≈ 3,000 h	×	By AlGaAs semiconductor laser	○	By AlGaAs semiconductor laser	○	Not known	?
Price	As low as possible	Practical level	○	High	×	High	×	Low price by mass production	△	Low price expected from mass production	?
Dimentional outline	As small as possible	Practical level	◎	Large	×	Medium	△	Small	○	Small	◎

◎ Fully satisfactory, ○ Practically satisfactory, △ To be improved, × Practically unsatisfactory
*1 RIN: Relative intensity noise

The argon ion laser and semiconductor laser-pumped YAG-SHG laser can produce an output power of 30 mW or more as required for optical recording, but are large in physical size, cannot provide high-speed modulation as required for optical recording, and need an external modulator. The direct SHG of semiconductor laser, where the wavelength of semiconductor laser is halved through a nonlinear optical device, provides high-speed modulation of optical output power. Although it is still low in optical power output, it has recently been studied at many research laboratories as a storage device laser in the near future. Since laser oscillation with CdZnSe was confirmed for the first time in 1991[3], II-VI compound short-wavelength semiconductor lasers are drawing great expectations as ideal short-wavelength lasers in the future. It will be several years later, however, that the direct SHG of semiconductor lasers and II-VI compound short-wavelength semiconductor lasers are commercialized. The authors decided to use the argon ion laser and semiconductor laser-pumped YAG-SHG laser with sufficient optical power output as light sources for the optical disk evaluating apparatus.

3.1.2 Argon ion laser

Argon ion lasers have such problems as short lifetime, high price and large size, but they provide sufficient optical power output, have good optical quality of output beam such as wavefront and spatial mode, and are suited for optical storage devices. An air-cooled Omnichrome Model 543 argon ion laser was selected to reduce the overall size of the apparatus. The laser oscillation line was set at 515 nm which is closest to the wavelength of the semiconductor laser-pumped YAG-SHG laser described later. Since no reports were available about the noise of such a small argon ion laser, the output light of the device was received with a photodiode, and the noise was measured with a spectrum analyzer. The noise level of the laser at the frequency of 3.7 MHz was about 10^{-14}/Hz when expressed in relative intensity noise (RIN). This is a practical noise level for an optical storage device.

3.1.3 Semiconductor laser-pumped YAG-SHG laser

The semiconductor laser-pumped YAG-SHG laser has an oscillation frequency of 530 nm and provides an optical output power of 30 mW or more. A semiconductor laser-pumped solid-state laser has a smaller size, including the power supply, and long lifetime compared with a gas laser, and is considered a viable substitute for the argon ion laser. A semiconductor laser-pumped YAG-SHG laser was trially manufactured along with the argon ion laser for the purpose of reducing the overall size of the optical storage device. The use of such a solid-state laser as the semiconductor laser-pumped YAG-SHG laser in an optical storage device is believed to encounter the following problems:

(1) Since the solid-state laser has a longer emission lifetime and higher gain than the gas laser, multiple modes oscillate at the same time, and their competition is likely to produce noise. Some mode selecting device must be placed in the optical cavity.

(2) When the driving current of the pumping semiconductor laser is increased, a wavelength shift occurs to change the pumping efficiency of YAG. The optical output power of the SHG laser does not necessarily increase. It is therefore difficult to stabilize the optical output power of the YAG-SHG laser even when feedback from the optical output power is used for the control of semiconductor laser driving current.

Fig. 2 shows the configuration of the prototype semiconductor laser-pumped YAG-SHG laser fabricated for an optical storage device in consideration of the above problems. The YAG-pumping semiconductor laser (Sony SLD-304) is of the AlGaAs wide-stripe type with a wavelength of 809 nm and optical output power of 1 W. The laser output beam passes through the collimating lens and the anamorphic prism and illuminates on the YAG rod. The YAG rod is 3 mm in diameter and 8 mm in length. The end of the YAG rod on which the semiconductor laser beam falls is spherically ground to R = 120 mm and coated to transmit the 809-nm semiconductor laser light and to reflect the 1.06-μm YAG laser light and the 530-nm YAG-SHG light. The SHG device is KTP and 5 mm long. The end of KTP is coated to reflect the 1.06-μm light and transmit the 530-nm light. The optical cavity of the YAG laser is formed between the end coating of YAG and that of KTP. As mode selecting device, a quarter wave plate to 1.06 μm is installed between YAG and KTP.

This configuration achieved single-mode oscillation at 530 nm and 30 mW. The noise level was 10^{-4}/Hz when expressed in RIN and confirmed the usability of the laser for optical storage devices. The configuration of the optical system tended to increase noise with time and made it difficult to maintain noise stably at a low level for a long period of time. The probable cause was the effect of heat on the YAG rod. This problem will be solved by optimizing the configuration of the optical system. The use of YVO_4 with a mode selection function is studied as material for the laser rod itself.

A new control method was devised to avoid the difficulty of stabilizing the optical output power of conventional semiconductor laser-pumped YAG-SHG lasers. The control method uses a program that keeps the laser chip temperature constant with respect to the semiconductor laser current by a built-in Peltier device and ensures a linear relationship between the semiconductor laser driving current and the SHG optical output power. Un-

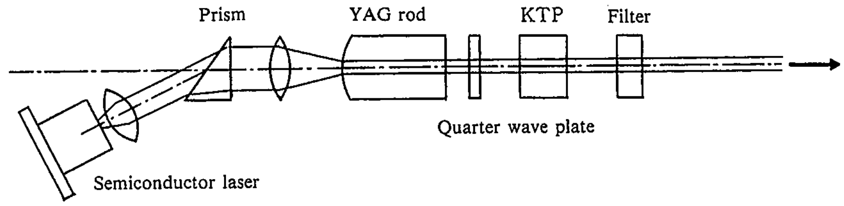

Fig. 2 Configuration of semiconductor laser-pumped YAG-SHG laser

der this condition, feedback of the SHG optical output power to the semiconductor laser driving current helped to achieve a stable optical output power with variations of ± 10% over a long period of time as is possible with argon ion lasers.

The generation of noise hampers the substitution of a present semiconductor laser-pumped YAG-SHG laser for an argon ion laser in an optical storage device. If measures are taken to reduce noise and stabilize optical output power as found to date, performance similar to that of the argon ion laser can be obtained. Considering its size and stability, the semiconductor laser-pumped YAG-SGH laser is expected to replace the argon ion laser in the future as light source for optical storage devices. For the time being, the argon ion laser is adopted on the apparatus for evaluating optical disks. The optical disk evaluating apparatus is designed to replace the argon ion laser with a semiconductor laser-pumped YAG-SHG laser in the future.

3.2 Apparatus for evaluating optical disk with short-wavelength light source

Table 3 gives the specifications of the prototype short-wavelength light source optical disk evaluating apparatus. Since the wavelength is short and the light source is large, the optical system has the light source separated from the movable optical pickup. Except for this difference, the apparatus is similar in configuration to the conventional magneto-optical storage device. The special considerations taken into account are described below.

Table 3 Specifications of apparatus for evaluating short-wavelength light source optical disks

Light source	Laser	Argon ion laser (514.5 nm) and semiconductor laser-pumped YAG-SHG laser (530 nm)
	Optical power	30 mW (±2%)
	Optical modulation	By acusto-optic modulator
	Wave aberration	≤ λ/20
Optical pickup	Objective lens	NA = 0.46 (525 nm)
	Fine actuator	Plate spring type
	Error detection	Focusing: Astigmatism method Tracking: Push-pull method
	Signal detection	Differential detection
	Seek mechanism	By linear motor
Spindle		Speed: ~ 36000 rpm, Speed variation: ≤ 0.01%
Bias magnetic field		1 kOe maximum

3.2.1 Disk

High-density optical recording with a short-wavelength light source calls for the track pitch to be reduced in proportion to the wavelength. The present ISO standard specifies a track pitch of 1.6 μm for 130-mm magneto-optical disks. When calculated according to the principle of wavelength similarity the track pitch can be 1.6 μm multiplied by 515 nm/780 nm = 0.74, or 1.2 μm. The track groove depth was set at 0.4 μm. The track groove pitch and depth will be reduced further, depending on experimental results.

3.2.2 Optics for optical beam modulation

Fig. 3 shows the configuration of an optical modulator and an optical system for the laser beam alignment. Assuming a maximum recording frequency of 10 MHz, the minimum pulse duration is 50 ns, and the modulator takes at least 10 ns rise time.

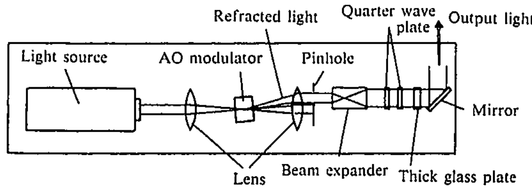

Fig. 3 Optical modulator and beam position adjust mechanism

External modulators for laser light generally use electro-optic (EO) and acusto-optic (AO) effects. Electro-optic modulators provide high-speed modulation, but requires high voltage to accommodate a large extinction ratio and grows in size, including the power supply. Also, the plane of polarization of modulated light rotates. Because of these problems of electro-optic modulators, an acusto-optic modulator (Crystal Technology Model 3200-121) was adopted.

To raise the response speed of the acusto-optic modulator, the laser beam is focused on the modulator by a long-focal length lens and is then collimated by a lens of the same focal length. A large extinction ratio is provided by using diffracted light at the sacrifice of light transmission efficiency. The optical output power after modulation must be accurately maintained at the two levels, write and read levels. The argon ion laser and the semiconductor laser-pumped YAG-SHG laser both have optical output power variations of about 10%. The peak value (for writing) and bottom value (for reading) of optical output power after modulation are kept within 2% by separably feeding back the peak and bottom values of acusto-optic modulator electric signals.

3.2.3 Wavefront control and positional alignment

The total wavefront distortion required of optical storage devices is said to be λ/14. This means that the wavefront distortion of the light source must be limited to λ/20 or less. Since the wavefront distortion of the light source and modulator used is not designed for optical storage devices, a beam expander with a pinhole is installed after the modulator to reduce the wavefront distortion. To align the output beam, a polarization rotator consisting of two quarter wave plates, a beam positioner with 1-cm-thick parallel glass plates and a beam angle adjuster with rotatable mirror are installed after the beam expander. When observed with a Mach-Zehnder interferometer (Wyco Ladite), the wavefront distortion is less than λ/20 and meets the original specification.

3.2.4 System Configuration

The optical pickup is made integral with a fine actuator for both focusing and tracking and a detector for both magneto-optical and error signals, and is driven by a linear motor. The numerical aperture (NA) of the objective lens is set at 0.46 (λ = 525 ± 15 nm).

The configuration of the apparatus is as shown in **Fig. 4**. The system is assembled on a 1.8 m by 0.9 m vibration-isolating table, and the light source, optical modulator and beam position adjusting mechanism are configured on a smaller dedicated vibration-isolating table.

3.3 Short-wavelength optical recording medium

The TbFeCo medium is widely used for magneto-optical recording disks. Since it decreases in the Kerr rotation angle with decreasing optical wavelength, it may be written with such a short-wavelength light source, but read signals will become too weak

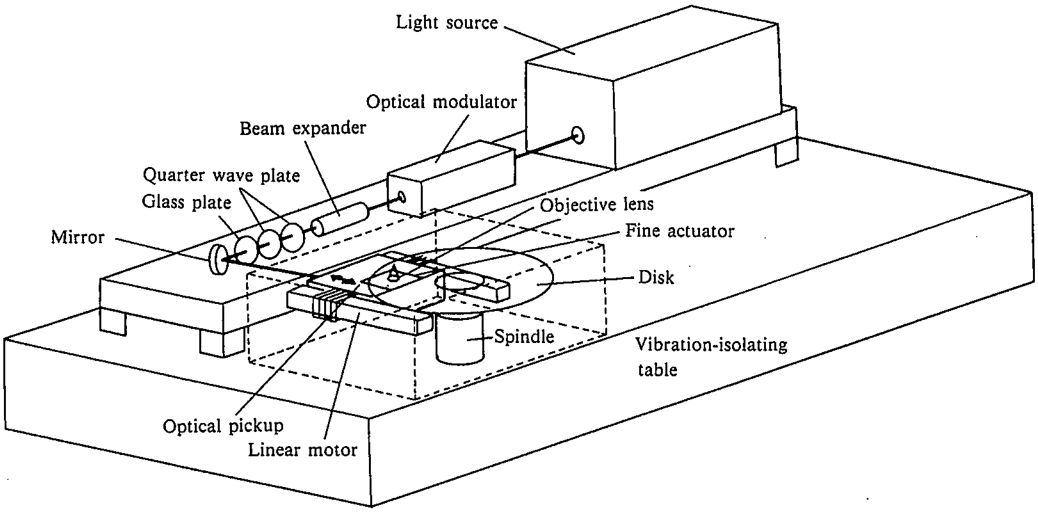

Fig. 4 Configuration of short-wavelength optical disk evaluating apparatus

to be practical. The following three magneto-optical recording media considered usable at short wavelength:

(1) TbFeCo material changed in composition or exchange-coupled with another material of large Kerr rotation angle at short wavelength
(2) Artificial superlattice film like platinum/cobalt multilayer film
(3) Bismuth-substituted magnetic garnet film

These short-wavelength optical recording materials have different features, and their relative advantages are not fully clear yet. The authors focused attention on a BiGa-substituted Dy-iron garnet film and experimented on this material.

The BiGa-substituted Dy-iron garnet has an oxide crystal structure, is formed on a gallium-gadolinium-garnet (GGG) substrate by epitaxial growth, exhibits an extremely large Faraday rotation angle, and is known to show good properties as a short-wavelength magneto-optical recording medium[4]. When deposited on a glass substrate to obtain a large area, the medium assumes not a monocrystalline but a polycrystalline structure. When a film is deposited on a glass film by a conventional process, its crystal grain size is more than 10 μm, which is too large for optical recording with a beam spot diameter of less than 1 μm. To write information with a spot diameter of less than 1 μm, the crystal grain size must also be less than 1 μm.

To utilize the characteristic of this recording medium that its Faraday rotational angle is large in short wavelength region of 500 nm, the authors studied the way of making the grain size of a thin film formed on the glass sabstrate smaller than the record bit. It was found as a result that the grain size can be reduced to less than 1 μm by adding copper to the material and heat treating it[5].

To evaluate the magneto-optical recording characteristics of the medium, a copper-added Bi-substituted garnet film was sputtered on the grooved glass substrate described in 3.2.1, and was investigated for its write and read performance using the prototype optical disk evaluating apparatus. An example of read waveform of signals recorded at a frequency of 400 kHz is shown in **Fig. 5**. Probably because its fabrication conditions are not optimal yet, the tested film produced too high, overlapping noise to be used for a storage medium. It was confirmed, however, that this material has a high potential to become a future magneto-optical recording medium with short wavelength. Optimization of film deposition conditions is considered the only requirement for high-density recording with this medium.

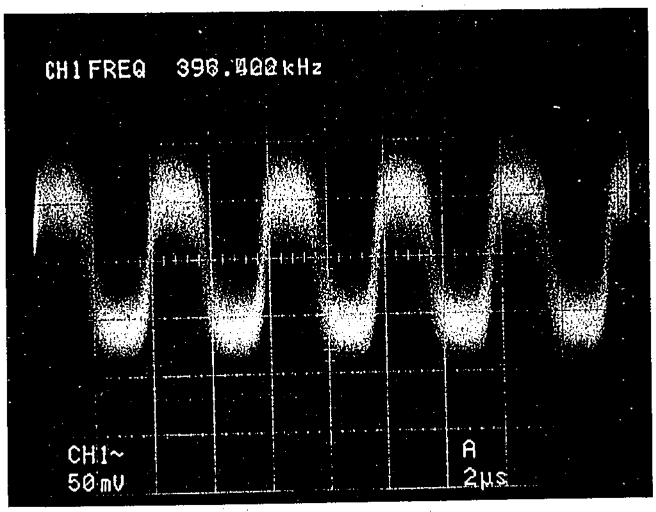

Fig. 5 Example of write and read signals as measured with optical disk evaluating apparatus by using short-wavelength light source
(write frequency: 400 kHz, carrier-to-noise ratio of read signal: 30 dB)

4. Conclusions

As basic research aiming at a third-generation high-density optical storage device, a prototype short-wavelength light source for optical storage devices and short-wavelength optical disk evaluating apparatus were made, and write and read experiments were conducted by using BiGa-substituted Dy-iron garnet films with high sensitivity at short wavelength. The experimental results obtained may be summarized as follows:

(1) Short-wavelength light source

At present, the semiconductor laser-pumped YAG-SHG laser has the highest potential as a light source for short-wavelength optical storage devices. The laser achieved stability of ±2%, including an optical modulator, and yielded satisfactory performance for an optical storage device. Noise must be reduced after further research, however.

Other semiconductor laser-pumped SHG lasers and II-VI compound short-wavelength semiconductor lasers are expected to emerge as future light sources. Commercialization of these lasers is an essential condition for manufacturing low-cost and stable optical storage devices.

(2) Magneto-optical storage device with short-wavelength light source

An external modulator and an elaborate optical system to remove wavefront distortion were used, but the original purpose of evaluating an optical disk with a short-wavelength light source was accomplished. If a semiconductor laser-pumped YAG-SHG laser is used as the light source, it is considered possible to assemble the entire apparatus in a housing of practically small size as secondary storage device for computers.

(3) Short-wavelength magneto-optical recording medium

A prototype optical disk was made using a BiGa-substituted Dy-iron garnet film and was evaluated as to its characteristics. The optical disk has a still low C/N ratio, but its write and read characteristics are confirmed, and the possibility of high-density optical recording is ascertained. The authors intend to continue their research on the present medium as well as other short-wavelength magneto-optical recording media.

5. Acknowledgments

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