A new magnetic recording method using millimeter/terahertz waves !!
— Demonstration of focused millimeter assisted magnetic recording —

１． Presenters

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２． Key points of the work

- With increasing amounts of information, to achieve high-density recording in the future, researchers succeeded in proving the concept of "focused millimeter-wave assisted magnetic recording" as a new magnetic recording method that uses millimeter waves.
- Focusing on epsilon iron oxide (ε-Fe_2O_3) and metal-substituted ε-Fe_2O_3, which are candidates for magnetic fillers of future magnetic recording tapes and also possess high-frequency millimeter-wave absorption properties for the Beyond 5G Era, they prepared magnetic films of ε-Fe_2O_3 and constructed a focused millimeter-wave generator using terahertz (THz) light source, and experimentally demonstrated "focused millimeter-wave assisted magnetic recording".
- The new recording method will enable the use of smaller magnetic nanoparticles for the magnetic recording media, and the recording capacity is expected to drastically increase.

３． Overview of the work

A research group consisting of Professor Shin-ichi Ohkoshi of the School of Science, the University of Tokyo, Associate Professor Makoto Nakajima of Institute of Laser Engineering, Osaka University, and Manager Masashi Shirata and General Manager Hiroaki Doshita of Recording Media Research & Development Laboratories, FUJIFILM Corporation, collaborated with Professor Hiroko Tokoro of University of Tsukuba, Emeritus Professor Seiji Miyashita of the University of Tokyo, and Takehiro Yamaoka of Hitachi High-Tech Corporation, to successfully develop a new magnetic recording method, "millimeter wave magnetic recording", using millimeter and terahertz waves.

In the era of Big Data and the Internet of Things (IoT), data archiving is a key technology. From this viewpoint, magnetic recording tapes [1] are actively used in cloud services and data archives for business purposes because they guarantee long-term data storage, low power consumption, and low cost. Consequently, the demand for magnetic recording tapes is growing. To archive an enormous amount of data, recording density needs to be increased. In this work, Professor Ohkoshi and colleagues proposed a new magnetic recording methodology, "Focused Millimeter wave–assisted Magnetic Recording, F-MIMR," to achieve millimeter-wave magnetic recording. To test this methodology, magnetic films were prepared using epsilon iron oxide [2], which is drawing attention as a magnetic filler for future magnetic recording tapes and also as a millimeter-wave absorber for Beyond 5G [3] networks, and constructed a focused millimeter wave generator using terahertz (THz) light. Irradiating the focused millimeter wave to epsilon iron oxide switched its magnetic pole direction, and magnetic field writing was confirmed. F-MIMR is an innovative magnetic recording method for the Beyond 5G Era, combining light/electromagnetic waves of Beyond 5G networks and magnetic recording. Thus, F-MIMR could contribute to raising the magnetic recording density.

The results of this research will be published online in *Advanced Materials* on October 8, 2020, Japan time.

４． Details of the work

Millimeter wave technology is expected to play a significant role in the era of Internet of Things (IoT). Millimeter waves (30–300 GHz) [4] have potential in broadcasting wireless communications, wireless data transmissions between cellular base stations, and traffic monitoring sensors in intersection areas for advanced driver assistance systems. For example, millimeter waves at an 80-GHz frequency are widely used for car radars. Meanwhile, magnetic recording is drawing attention as a sustainable data storage system in the Big Data era. To further enhance the recording capacity to archive an exponentially increasing amount of data, the magnetic particle size must be reduced. However, as magnetic particles become smaller, the thermal stability of the magnetization decreases (the problem of superparamagnetism). In order to avoid the problem of superparamagnetism, enlargement of the magnetic anisotropy is necessary. Consequently, current magnetic recording heads cannot write against the strong magnetic anisotropy. This problem is called the “magnetic recording trilemma” and is common for magnetic recording media, including hard disk drives and magnetic tapes. To resolve the trilemma problem, several types of recording methods have been proposed such as heat-assisted magnetic recording and microwave-assisted magnetic recording.

Professor Ohkoshi and colleagues focused on epsilon iron oxide for two main reasons. First, it exhibits high-frequency millimeter wave absorption in a wide frequency range of 35 to 222 GHz due to the zero-field ferromagnetic resonance and is expected to be used for Beyond 5G applications. Second, it can also maintain spontaneous magnetization due to ferrimagnetism even with a single nanometer size particle. In this study, they prepared magnetic films based on metal-substituted epsilon iron oxide and propose a new recording methodology “Focused Millimeter Wave–Assisted Magnetic Recording (F-MIMR)” based on a novel concept of “millimeter wave magnetic recording” (Figure 1).

For the demonstration, magnetic films based on gallium-titanium-cobalt–substituted epsilon-iron oxide (GTC-type ε-iron oxide: $\varepsilon\text{-}Ga_{0.23}(TiCo)_{0.05}Fe_{1.67}O_3$) nanoparticles were prepared on a glass subustrate (Figure 2). Additionally, an intense millimeter-wave generator was constructed using terahertz light as a light source, and a millimeter-wave focusing ring [5] was designed using electromagnetic field analysis simulation [6] and fabricated on the surface of the magnetic film [6] to focus the millimeter wave corresponding to the resonance frequency of GTC-type ε-iron oxide. As shown in Figure 3, the magnetization direction of the film was aligned along the +*Z*-direction. Then, an external magnetic field of 3.4 kOe, slightly weaker than the coercive field value of 4.9 kOe, was applied toward the opposite direction (−*Z*-direction). The sample was irradiated by a focused millimeter wave.

The atomic force microscopy (AFM) [7] image of the sample after irradiation of the focused-millimeter wave showed the geometry of the ring. In the magnetic force microscopy (MFM) image, a dark shadow was observed near the focusing ring. The observed MFM image agrees well with the magnetic field distribution map simulated by electromagnetic field analysis, indicating that the magnetization was flipped by the assistance of the focused-millimeter wave. This is the first reported observation of a permanent magnetic pole flip by millimeter wave irradiation.

As an additional demonstration, a magnetic film placed face-to-face with the millimeter wave–focusing ring fabricated on Si wafer was irradiated with a millimeter wave. In the MFM image of the magnetic film after irradiation of the focused-millimeter wave, magnetization reversal was observed at the millimeter wave focused area.

To understand the spin dynamics of F-MIMR, the time evolution of all of the spins in an epsilon iron oxide nanoparticle were calculated using the stochastic Landau-Lifshitz-Gilbert model [8]. Simulation results showed that magnetization reversal instantly occurs by irradiating a millimeter wave of the resonance frequency.

Millimeter wave magnetic recording technique enables to reduce the particle size of the magnetic material and solve the magnetic recording trilemma, leading to the increase of the recording capacity. The transition energy of the millimeter wave is *ca*. 1/5000 compared to that visible light. Therefore, heat-up is avoided in millimeter wave–assisted magnetic recordings, which is very important for magnetic recording tapes that use organic resin for the base film.

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５． Publication Journal

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６． Precautions

Publications prior to 7:00 pm on October 8th, 2020 (Thu), Japan Standard Time (noon on October 8th, 2020 (Thu), Central European Summer Time) are prohibited.

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８. Glossary

（１）　Magnetic recording tapes

Magnetic recording tapes are the earliest known magnetic recording media (since the 1950s). Japanese companies have monopolized the production of tape media and, nowadays, magnetic tapes are mainly used as the recording media for archiving. Due to the guarantee for long-term recording and low cost, demands for magnetic tapes are growing rapidly in a variety of areas, including insurance companies, banks, broadcasting stations, and web service companies.

（２） Epsilon iron oxide (ε-Fe_2O_3)

Professor Shin-ichi Ohkoshi and his colleagues successfully synthesized a single phase of epsilon iron oxide in 2004 by nanoparticle synthesis method. They reported that epsilon iron oxide possesses a crystal structure different from the conventional phases such as gamma (γ) and alpha (α) phases, and exhibits the largest coercive field among metal oxides at room temperature (20 kOe). In addition, epsilon iron oxide has been highlighted as one of the candidates for the next generation of magnetic particles for magnetic tapes in the roadmap of the information storage industry consortium (INSIC), a global consortium of the magnetic tape industry.

（３） Beyond 5G

Beyond 5G is the sixth and subsequent communication standard following the fifth generation of mobile communication system (5G; 3.7 GHz, 4.5 GHz, 28 GHz in Japan), which began to be used in 2019. Millimeter waves, which are higher frequency electromagnetic waves, are expected to be used in Beyond 5G networks.

（４） Millimeter waves

Millimeter waves are electromagnetic waves with a wavelength of 1 mm to 10 mm and a frequency range of 30 to 300 GHz. At present, millimeter-wave car radars are widely used, and practical applications of millimeter waves for wireless communication are being promoted as a next-generation high-speed wireless communication system. Epsilon iron oxide absorbs high-frequency millimeter-waves due to the precession of the magnetization, and is expected as a millimeter-wave absorber for high-speed wireless communications and automated driving support systems.

（５） Focusing ring

Focusing ring is a metallic ring with a gap. When electromagnetic waves, such as terahertz light, are irradiated to the focusing ring, a circumferential current flows, causing a resonant phenomenon that enhances the intensity of the electromagnetic waves at a particular frequency.

（６） Electromagnetic field analysis simulation

Electromagnetic field analysis is a simulation that theoretically calculates the electric and magnetic field distributions generated by electromagnetic waves.

（７） Atomic force microscopy and magnetic force microscopy

Atomic force microscopy detects the interatomic force between the probe and the sample to show the geometries of the sample surface. On the other hand, magnetic force microscopy detects the magnetic force between the probe and the sample to show the magnetic state of the sample surface.

（８） Stochastic Landau-Lifshitz-Gilbert model

Stochastic Landau-Lifshitz-Gilbert model is a theoretical model that incorporates stochastic noise as temperature effects into the Landau-Lifshitz-Gilbert equation, an equation that describes the precession of the magnetization in magnetic materials. F-MIMR was theoretically demonstrated using a model taking into account all of the individual spin movements in the nanoparticle.

9． **Figures**

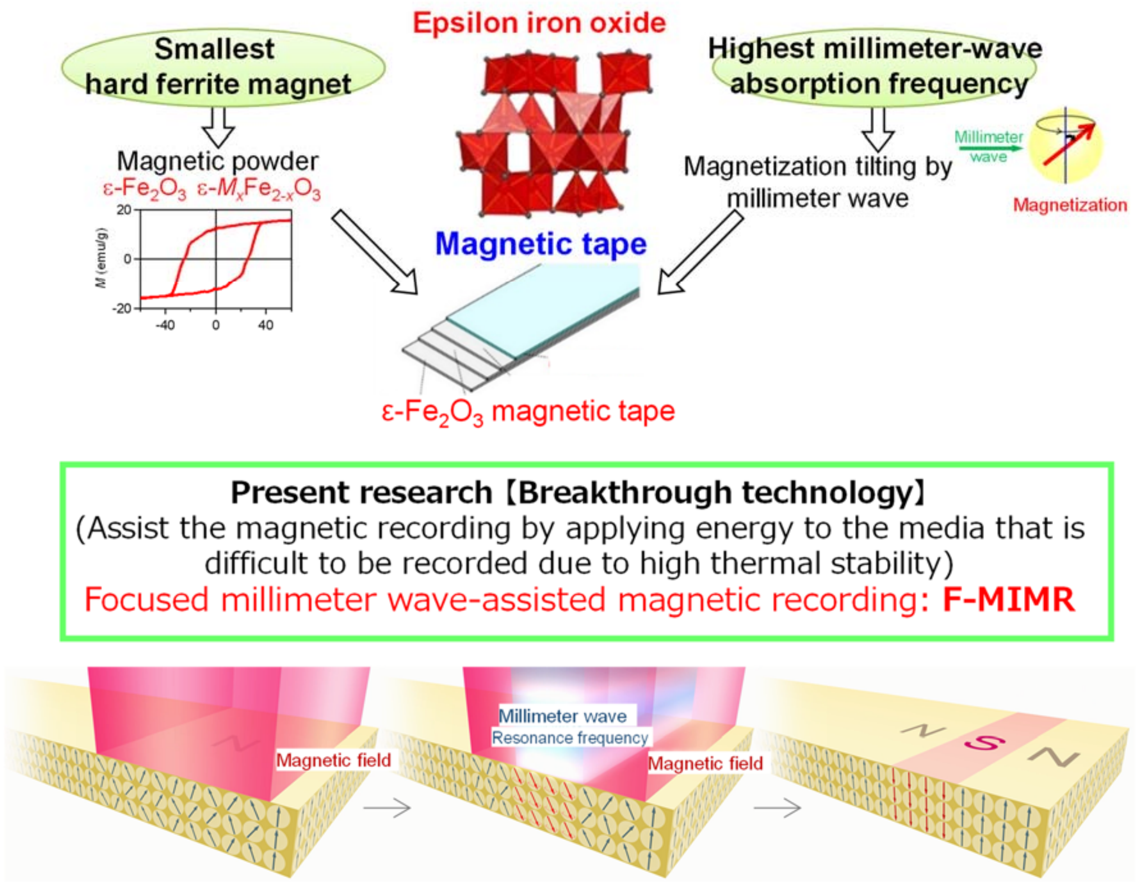

Figure 1. Concept of "Focused millimeter wave-assisted magnetic recording" (F-MIMR). F-MIMR is a recording system using the characteristics of the world's smallest hard ferrite, epsilon iron oxide, which exhibits high-frequency millimeter-wave absorption. The necessary magnetic field for magnetization reversal is reduced by the millimeter wave irradiation only during recording.

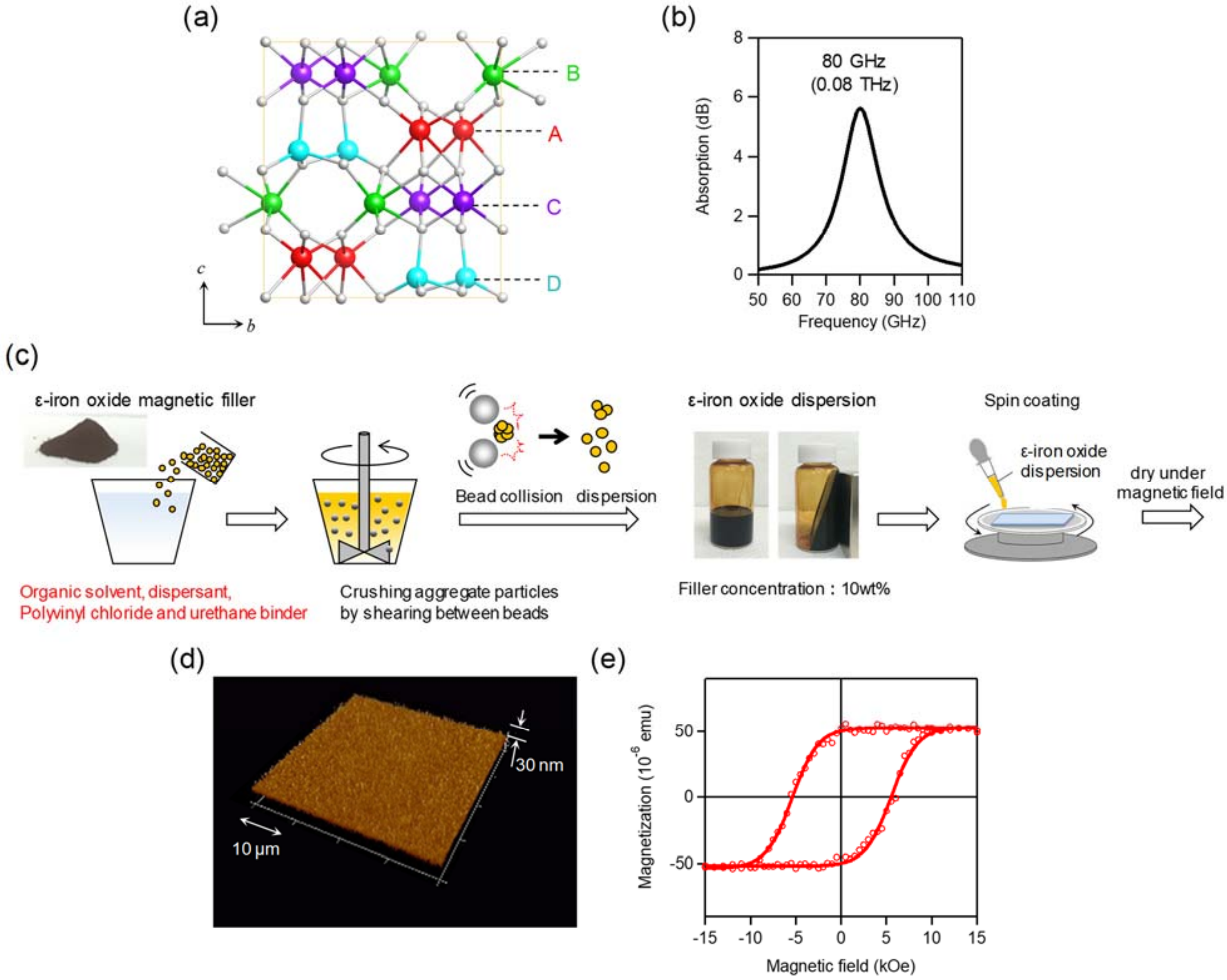

Figure 2. Physical properties of GTC-type ε-iron oxide （ε-$Ga_x(TiCo)_yFe_{2-x-2y}O_3$） and preparation of magnetic film. (a) Crystal structure of GTC-type ε-iron oxide. Red, green, purple, light blue, and gray balls represent Fe atoms at A, B, C, and D sites, and oxygen atoms, respectively. (b) Millimeter wave absorption spectrum obtained from THz-time domain spectroscopy measurement. (c) Preparation process of the ε-iron oxide dispersion and ε-iron oxide film. (d) 3D topological AFM image of the magnetic film. (e) Magnetic hysteresis loop of the film when the external magnetic field is applied to the out-of-plane direction. The data in the figure are for the sample with a composition of $x = 0.23$ and $y = 0.04$.

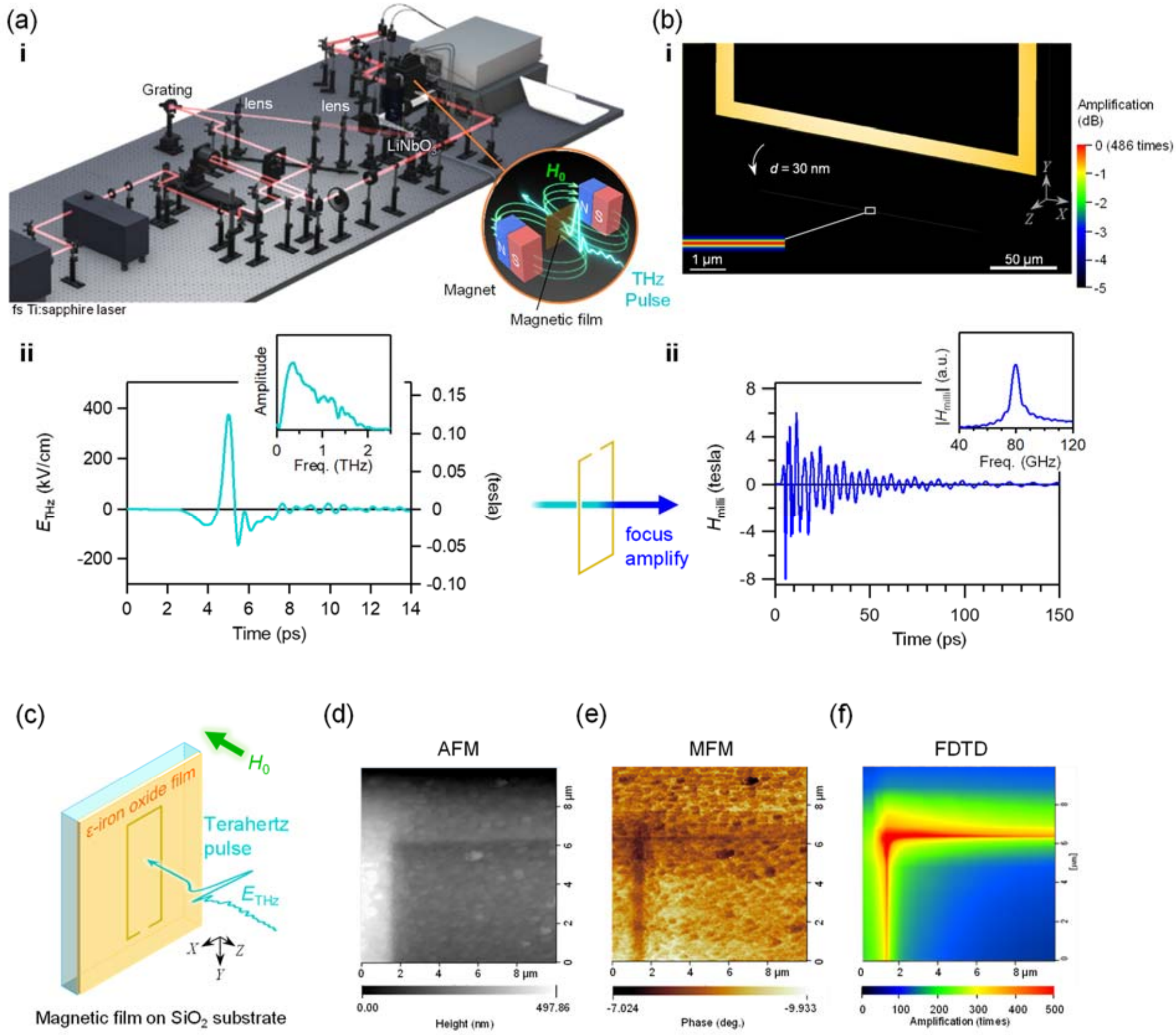

Figure 3. Setup of focused millimeter wave–assisted magnetization reversal, design of the focusing ring, and the demonstration experiment. (a) (i) Schematic of the intense terahertz light generation from the $LiNbO_3$ crystal. Inset shows the configuration of the film, external magnetic field (H_0), and terahertz pulse. (ii) Observed electric field of the terahertz pulse in the time domain and its Fourier-transformed spectrum. (b) (i) Electromagnetic field analysis of the Au ring (735-μm long and 265-μm wide with a 14.7-μm ring width, a 58.8-μm gap, and a 0.1-μm thickness). Colored areas show the intensity of the millimeter wave magnetic field (H_{milli}) at 30 nm below the focusing ring. (ii) The calculated time dependence of H_{milli} at the inner corner of the ring. Inset is the frequency spectrum of $|H_{milli}|$. (c) Schematic configuration of the ring on the magnetic film, and directions of H_0 and terahertz pulse. (d) AFM image at the corner of the ring after 1-shot terahertz pulse irradiation under H_0 of 3.4 kOe. Color scale indicates the height. (e) MFM image of the same position as d. Color scale indicates the magnetic fluxes going out of (white) and into (black) the page, corresponding to the N- and S-poles, respectively. (f) Calculated distribution of H_{milli} at the inner corner of the ring.