SYMPOSIUM J
Magneto-Optical Materials for Photonics and Recording

November 29 - December 2, 2004

Chairs

Koji Ando
AIST
Nanoelectronics Research Institute
Tsukuba Central 2
Umezono 1-1-1
Tsukuba, Ibaraki, 305-8568 Japan
81-29-861-5455

William A. Challener
Seagate Research
1251 Waterfront Pl.
Pittsburgh, PA 15222
412-918-7197

Richard Gambino
Lab for Magneto-Optic Matls & Engr
Stony Brook University
Stony Brook, NY 11794-2275
631-632-9513

Miguel Levy
Physics Dept.
Michigan Technological University
Houghton, MI 49931
906-487-2084

Symposium Support
Seagate Technology LLC

Proceedings to be published in both
book form and online
(see ONLINE PUBLICATIONS at www.mrs.org)
as volume 834
of the Materials Research Society
Symposium Proceedings Series.

* Invited paper
TUTORIAL

FT J: Heat-Assisted/ Hybrid Recording - The Next Generation in Magnetic Recording
Monday November 29, 2004
1:30 PM - 5:00 PM
Berkeley (Sheraton)

The continued increase in information-storage densities in magnetic hard disk drives is facing a fundamental challenge. This superparamagnetic limit is a consequence of the instability in the magnetization of grains in magnetic media as bit dimensions; therefore, grain volumes are scaled down. Heat-assisted or hybrid recording is one of the solutions being put forward to overcome this limit. This tutorial will include the formation of small optical, head integration, and media requirements. Many materials challenges feed into each of these elements and will be described in this tutorial, as will current work in the field.

Instructor:
T.E. Schlesinger
Carnegie Mellon University

SESSION J1: Magnetic Photonic Crystals I
Chairs: Koji Ando and Miguel Levy
Tuesday Morning, November 30, 2004
Berkeley (Sheraton)

8:30 AM J1.1
Magnetophotonic Crystals, Mitsuteru Inoue, Dept. of Electrical & Electronic Eng., Toyohashi University of Technology, Toyohashi, Aichi, Japan.

Magnetophotonic crystals, which are one-, two-, or three-dimensional periodic composites of macroscopic magnetic media of different refractive indices. Because of their periodic structures, the magnetophotonic crystals affect the propagation of light providing the photonic bandgap, localized modes in the gap and large enhancement of magneto-optical properties associated with the localization of light. For higher modes of light, the propagation properties of light can be changed by controlling the direction of magnetization with a magnetic filed. In this paper, based mainly on our recent studies, preparation of magnetic ferrite base one-, two-, and three-dimensional magnetophotonic crystals is presented and their fundamental linear and nonlinear optical and magnetooptical properties are described. Some applications of the media for optical communication and light modulation will also be introduced.

9:00 AM J1.2
Magnetic Photonic Crystals as Artificial Magnetoelectric Media, Alex Figotin and Ilyn Vitebsky; Mathematics, University of California at Irvine, Irvine, California.

Usually, plane electromagnetic waves in homogeneous or periodic heterogeneous media display the fundamental property of spectral symmetry w(k) = w(-k). This relation is a direct consequence of the time reversal and/or space inversion symmetry. If neither of the symmetries applies, the medium can support spectral asymmetry, which implies that plane waves propagate in one direction faster or slower than in the opposite direction. In media with linear magnetoelectric effect such a phenomenon has been known for decades. The problem with magnetoelectric crystals though is that the degree of electromagnetic spectral asymmetry is negligible (0.001 or less). This situation is further aggravated by complicated and often uncontrollable domain structure of natural magnetoelectric materials. All the above problems can be avoided in magnetic photonic crystals, which are periodic arrays of ferromagnetic and other dielectric components. Indeed, the presence of a ferromagnetic constituent can eliminate the time reversal from the macroscopic symmetry group of the periodic array. The space inversion can always be removed by proper choice of the periodic structure geometry, even if each individual constituent is a centrosymmetric material. In this way, the macroscopic symmetry of magnetic photonic crystal can always be made compatible with that of a magnetoelectric crystal. Such a composite will not display any static magnetoelectric effect, but dynamically it can behave like an artificial magnetoelectric medium with huge magnetoelectric response and strong electromagnetic spectral asymmetry, unachievable in any natural material. At least at frequencies below 200 GHz, an appreciable spectral asymmetry can be achieved in periodic stacks composed of common ferrimagnetic and other dielectric components (A. Figotin and I. Vitebsky, Phys. Rev. E63, 066609, 2001). Strong spectral asymmetry can result in the phenomenon of electromagnetic unidirectionality (A. Figotin and I. Vitebsky, Phys. Rev. B67, 2003). A unidirectional periodic medium, being perfectly transparent for plane electromagnetic waves propagating in a certain direction, "freezes" the radiation of the same frequency propagating in the opposite direction. At the frequency of the frozen mode, the electromagnetic radiation incident on the surface of a unidirectional photonic slab can pass inside the slab with little or even no reflectance, where it gets trapped in the form of a coherent frozen mode with gigantic amplitude and zero group velocity.

9:30 AM J1.3
Magneto-Optical Response of a One-Dimensional All-Garnet Photonic Crystal in Transmission and Reflection, Soen Kim and Alexander M. Grishin; Condensed Matter Physics, Royal Institute of Technology, Kista, Stockholm, Sweden.

We present spectra of transmittance, reflectance, Faraday and Kerr rotation for a periodic garnet multilayer structure (magneto-photonic crystal, MPC). The structure consists of eight quarter-wave layers of each bismuth and yttrium iron garnet and a four times thicker central bismuth iron garnet layer. The total thickness is around 1.5 μm and resonance wavelength is around 750 nm. The measurements in reflection were performed with a silver mirror deposited on top of the MPC. The rotation of the plane of polarization is enhanced strongly in reflection. The peak value obtained close to 750 nm, 18 deg. is about 4.5 times higher than if the light passes once through 1.5 μm of pure bismuth iron garnet. This also corresponds to more than three times enhancement of the polarization as compared to the same light transmitted through the MPC. Due to the absorption in bismuth iron garnet and the silver mirror, reflectance of only 13% was measured at resonance for the silver-coated MPC. The surface roughness with rms value of about 11 nm is sufficient to produce some depolarization. The resonance wavelength, about 5% for the silver-coated MPCs that work in reflection could be attractive for two-dimensional magneto-optical imaging. This depends on how quickly the magnetic field falls off with increasing distance from the magnetic sample under investigation as well as on the reflectance from the MPC and the sample.

10:30 AM J1.4

Engineering of garnet materials which are structurally compatible and possess high optical contrast with bismuth iron garnet B3Fe5O12 (BIG) was the main objective of this study. New La3Ga5O12 garnet (LGG) has been synthesized in the form of epitaxial films pulsed laser deposited on Gd3Ga5O12(111) single crystal. X-ray diffraction reveals epitaxial quality of LGG films: they are single phase, exclusively ([hhl] oriented and have a strong in-plane texture. Several TE and TM propagating modes have been detected from "dark" films about 2.5 μm thick LGG film by prism coupling technique. The refractive index was calculated to n = 1.98 at 655 nm (compared to 1.97 and 2.65 in Gd3Ga5O12 and B3Fe5O12 garnets correspondingly). Multiple light scattering in LGG filter creates a fine interference pattern in the spectrum recorded in the normal incidence geometry. These data were used to determine the wavelength dispersion of the refractive index. This follows Sellmeier's relation as n2 = 1 + 2.75*μ (1484nm)/μ2 and appears to be as small as 3.8% in the range from 400 to 1000 nm. Epitaxial BIG/LGG/GGG heterostructure was fabricated by pulsed laser deposition of LGG layer and the following deposition of B3Fe5O12 film by rf magnetron sputtering. In both processes we used stoichiometric ceramic targets. Giant Faraday rotation above 6 deg/μm, which is characteristic for BIG/GGG(111) films, has been preserved in BIG/LGG/GGG(111) structures.

10:45 AM J1.5
Observation of Enhanced Faraday Effect in Garnet-Based Magnetophotonic Crystals, Andrey A. Fedyanin, Oleg A. Aktsipetrov1, Daissuke Kobayashi2, Kazuhiro Nishimura2, Hiroanga Uchida3 and Mitsuteru Inoue4; 1Quantum Electronics Division, Quantum Electronics Division, Technology, Yokohama, Japan.

Photiconic crystals (PC) are dielectric microstructures with periodic modulation of refractive index in one or several spatial directions with period comparable with optical wavelength. The key feature of PC is the photonic band gap (PBG), which represents the prohibition of the propagation of light with the certain wave vector inside PC. PBG manifests itself in reflection and transmission spectra as the spectral region with full reflection and strongly suppressed transmission. One of the important issues regarding the application of PBG materials is the development of the magnetophotonic crystals (MPC), i.e. PC
formed from magnetic materials. MPC open up prospects for new spintronic devices utilizing magneto-optical effects. For example, the enhanced Faraday effect is observed in the phase-matched MPC with the half-wave-length-thick defect layer formed from magnetic material and the Bragg reflectors composed from nonmagnetic materials [1]. The practical difficulty of fabrication of magnetic Bragg reflectors is a serious control critical for the Bragg reflector quality. Another problem is the requirement of the transparent magnetic materials. Bi-substituted yttrium-iron-garnet (Bi:YIG) films are very convenient materials for the MPC fabrication due to low absorption in the visible and infrared regions, large magneto-optical response and small saturation magnetic fields. In this paper, the fabrication of magnetophotonic crystals formed from Bi-substituted yttrium-iron-garnet layers is reported. Enhancement of the Faraday rotation and transmission in the Bragg edge was associated with the multiple reflection interference and light nonreciprocity in MPC is experimentally observed. MPC are fabricated from several repeats (from 4 to 6) of quarter-wavelength-thick layers of Bi-substituted yttrium-iron-garnet fabricated on silicon oxide. The PBG is centered at about 950 nm. Coercivity of MPC is approximately 30 Oe for both configurations. For the tangential field application, saturating magnetic field is slightly above 100 Oe. For the normal configuration of the field application, saturating magnetic field is close to 2 kOe.

Transmission spectra of MPC have a low transmission region from 850 nm to 1100 nm corresponding to the PBG and the interference fringes outside it. At shorter wavelengths the transmission becomes smaller and tends to zero at approximately 550 nm correlating with absorption band of Bi:YIG. The spectrum of the Faraday rotation angle demonstrate the strong suppression inside the PBG and a peak at the long-wavelength edge of PBG at 1100 nm, where it enhances up to -0.7 degrees per micron at 1100-nm wavelength. [1] M. Inoue, K. Arai, T. Fujii, and M. Abe, J. Appl. Phys. 83, (1998) 6768.

11:00 AM J1.6
Nonlinear magneto-optics in garnet magnetophotonic crystals, Oleg A. Aktsipetrov1, Tatsuya V. Murzina2, Tatsuya V. Dolgov3, Andrey A. Fedyanin4, Mitsuteru Inoue5, Kazunori Nishimura2 and Hirokazu Uchida2; 1Department of Physics, Moscow State University, Moscow, Russian Federation; 2Toyohashi University of Technology, Toyohashi, Japan.


11:30 AM J1.8

Magneto-optical Bragg gratings are dielectric media possessing a periodic or semi-periodic spatial modulation of its optical or magneto-optical properties. In particular, the chirped magneto-optical Bragg gratings possess a spatial grating period that is strictly increasing or decreasing with the spatial coordinate along the grating, providing a flat plateau of high reflectance in the spectrum. The purpose of the work here presented is to show the possibilities opened by the application of magneto-optically induced perturbations in chirped Bragg gratings. We predict that by introducing such perturbations, the band blocking reflectance of the grating is opened up, allowing for a tunable narrow band transmission window in the spectrum. For Bragg gratings in waveguides, the necessary magneto-optical perturbation can be induced in a selective manner by means of a local change in magnetization along the grating. In particular, by changing the applied magnetic field using the effect of magnetic photonic crystals, the polarization plane is observed for the longitudinal NOMOKE configuration. Noticeable NOMOKE is observed in magnetization-induced third harmonic generation from magnetophotonic microcavities. The polarization rotation angle of NLBMR in the magnetic contrast up to 100 is observed in transversal NOMOKE configuration. This is worth noting the first realization of phase-matched magnetooptical response in the MPC. The nonreciprocal magnetooptical response is obtained with the phase-matching condition fulfilled at the PBG edge of the MPC. The giant magnetic effects in intensity and polarization rotation of the magnetization-induced SH and TH waves observed in garnet MPC and MMC open new applications of MPC as magneto-photon nonlinear-optical devices.
the structure, as well as the ellipticity changes occurring at the interfaces of the elements. We also discuss the inverse problem associated with magneto-optical gratings possessing a nonlinear optical response of the medium, and the impacts of nonlinearities on the optical transmission. This project was supported by the EU IST-510162 project PHAT.

11:45 AM J1.0
Electro-Optic and Magneto-Optic Photonic Bandgap Materials, Kevin Y. Zou1, Vanyun Wang1, Kewen Li1, Huajiang1 and Bethanie Hults-Bowden.
Dep. of Electronic and Computer Engineering, West Virginia University, Morgantown, West Virginia, USA; 2University of Minnesota, Minneapolis, Minnesota.

As communications and signal processing extend to higher data rates and faster speeds, conventional electronic signal processing methods are being stretched to their physical limits. Photonics appears to meet the requirements posed by the advanced data processing. Innovative photonic materials that enable high performance photonic devices are the foundation of the photonic technology. Photonic Bandgap (PBG) is an exciting new class of materials and electro-optic and magneto-optic materials are critical for active and passive photonic ICs. Very small photonic ICs can be assembled using vapor deposition methods. Thin semiconductor films made by a Metal-Organic Chemical Liquid Deposition (MOCLD) method. Electro-optic thin film, La-modified MgO and glass substrates and also onto buffered semiconductors were successfully deposited using MOCLD method. Several of these had successful rotations that were of device quality. Based on these high quality functional films, photonic bandgap structures such as waveguide isolator and electro-optic modulator were designed and fabricated.

SESSION J2: Magnetic-Photonic Crystals II
Chair: Koji Ando and Miguel Levy
Tuesday, November 30, 2004
Berkeley (Sheraton)

1:30 PM *J2.1
Room temperature photo-induced gyrotropic CdMgTe-CdMnTe semimagnetic semiconductor magneto-photonic micro-cavity. Sujay Banerjee1,2, Robert Frey,2, Geoff Broussard,2, Regis Andre3 and Christos Flytzanis1,1. Laboratoire Pierre Aigrain, Ecole Normale Superieure, Paris, France; 2Laboratoire Charles Fabry, Institut d'Optique, Universite Paris Sud, Orsay, France; 3Laboratoire de Spectrometrie Physique, Universite Joseph Fourier Grenoble, St Martin d'Heres, France.

Magneto-photonic micro-cavities with semimagnetic semiconductor nanostuctures were used to manipulate the state of quantum states when excited close to the exciton-polariton modes in the presence of a static magnetic field[1,2]. These gyrotropic features can also be photoduced by a circularly polarized light beam and large photo-induced Kerr rotation were obtained with moderate beam intensities in such micro-cavities when operated at the intermediate to weak coupling regime at low temperatures[3]. Here we report photo-induced polarization state configurations brought in by pump pulses of various polarization states for a probe beam incident onto a reflecting CdMgTe-CdMnTe magneto-photonic micro-cavity operating in the strong coupling regime at room temperature and compare the magnetic field induced and photo-induced contributions to the Kerr-induced magneto-optic polarizations. Kerr polarization rotations of several degrees are obtained at room temperature for pump beams of 1 micro-Joule/cm^2 in the absence of any magnetic field. The cavity and quantum confinement along with the spin exchange interaction play a key role here and a theory model is presented; the results are of interest as well for optical signal processing. The micro-cavity used in our experiment was grown by molecular beam epitaxy with the back and front cavity mirrors formed by stacking 21 and 1.5 layers thick CdMgTe/CdMnTe pairs and between them inserting three 8 nm thick quantum well separated by 40 nm wide gaps. The quantum well was composed of three 7-monolayer thick CdTe parts separated by two 2-monolayer thick intervals, such asymmetric micro-cavity configuration was chosen to maximize the polarization state rotations. In our experiment the photo-induced modifications of the photo-cavity on-cavity conditions and the resulting Kerr-effect, polarization and ellipticity change spectra brought in by a pump pulse having a definite polarization state and frequency were sensed with a linearly polarized probe pulse as a function of different parameters; the probe and pump beams were provided from two identical optical parametric generators pumped by a picosecond dye laser. The pump source generates large exciton polariton densities of the same polarization state and the pump pulse that set up an effective magnetization in the microcavity. I.M.S. Skolnick, T.A. Fisher, D.M. Whittaker, Semicond. Sci. Techn. 13: 643 (1998) 2.M. Haddad, R.Andre and R.Frey, Phys. Rev. B67, 045308 (2003) 3.IST-510162 project PHAT.

2:00 PM *J2.2
YIG Thin Film-Based Two-Dimensional Magnonic and Magneto-Photonic Crystals, Sergei A. Nikitov1, Yu A. Fedyanin2, Tailindent3 and Chen-Tao4.
1Institute of Radioengineering and Electronics, Russian Academy of Sciences, Moscow, Russian Federation; 2CIRIMAT-UMR CNRS 5085, Universite Paul Sabatier, Toulouse, France; 3Electrical Engineering and Computer Science, University of California, Irvine, Irvine, California.

Propagation properties of photonic crystals (PCs), stop-bands in particular, depend on the wavelength of the waves involved. Conventional PCs made of opals, colloidal particles, nanostructured films, etc., are normally studied in the visible light frequency range. Such PCs when operating in a microwave frequency range must carry large dimensions. In contrast, magnonic crystals (MCs) operating in the same microwave frequency range involve micron size-dimensions. The properties of microwave propagation in MCs are closely related to spin waves. In this paper, we report the first experimental realization of such MCs and present the results of our experimental study on spin waves propagation. From the practical point of view two-dimensional (2-D) MCs that utilize ferromagnetic waveguide with 2-D inhomogeneities of magnetization is preferred. We have fabricated yttrium-iron-garnet (YIG) film-based MCs in which 2-D arrays of holes are incorporated. The holes diameter and periodicity were chosen close to the half-wavelength of the magnetostatic spin wave (MSW) in order to fulfill Bragg reflection condition. The YIG film dimensions are 1.6 cm x 0.9 cm in area and 5 um in thickness. The periodic structures of holes were prepared by the photolithography method. Depth of holes was varied from 1.0 to 4.5 um in order to ensure sufficient changes in the magnetic parameters of the YIG film. The holes period was varied from 400 to 500 um. The stop bands for spin waves were found to be tunable by an external magnetic field. In addition, the MSW excitation band in the MC was found to decrease by order of magnitude. Specifically, the measured bandwidth was reduced from 400 to 500 MHz when the 2-D holes structure was incorporated in the YIG film. Furthermore, the propagation of optical waves in a magnetic waveguide with periodic domain structures, called magneto-photonic crystals (MPC), has been investigated. It is shown that conversion between propagating modes in 2-D periodic domain structures depends strongly on the parameters of the domain structure. Dispersion and anisotropic properties of the interacting modes and the dependence of the intensity of the converted mode on the parameters of the domain structures will be reported.

3:00 PM J2.3
Imaging by a Flat Lens and Slow Microwaves in Left-Handed Metamaterials, Placenta Vodol1,2, Emilian DiGennaro1,2, Patanjali V. Parimi1,2, Wentao T. Lu1,2 and Srinivas Sridhar1,2,1.
1Physics, Northeastern University, Boston, Massachusetts; 2Electronic Materials Research Institute (EMRI), Boston, Massachusetts.

We have demonstrated negative refraction of microwaves in a photonic crystal (PC) prism and imaging by a flat lens made of a dielectric photonic crystal using negative refraction of the microwave. The microwave image formation, including sub-wavelength resolution, are discussed. For a flat slab (Veselago) lens made of negative index media with refractive index -1, the formation of an image inside and outside the flat slab was obtained using ray tracing. Experimental results show that this is not the case in our flat lens, due to Bloch modulation of the waves inside the PC. An imaging theory explaining the image formation for these new lenses is described and is in good agreement with our experimental results. The experimental measurements on PC using a Microwave Transition Analyzer in order to measure the group velocity are carried out. By sending a 30ns width pulse with a carrier frequency ranging between 9 and 11 GHz, we analyze the signal delay due to the sample. The microwave group velocity is observed to be as low as 1/50 the speed of light, and is
consistent with the large dispersion observed in these metamaterials.
Collaborators: John Derov and Bev Turnerchen, AFRL, Hanscom.
Work supported by AFOSR and NSF-PHY-0098801.

3:15 PM J2.4

**Solvated Model of Two-Dimensional Magnetophotonic Crystal**

formed from magnetoactive dielectric sheets. Band structure of 2D
system parameters, such as angle of incidence or frequency. Additional
super-lenses and super-prisms that have in their basis PC’s structure.

3:15 PM J2.4

ehance significance of PCs for applications considerably [2]. It was
example of such devices [2]. The superprism effect consists in
example) but also in opportunity to control the PC properties by
especially for such promising and challenging structures like

3:45 PM J2.6

**Three-Dimensional Magnetophotonic Crystals Based on Synththetic Opal Fabrication and Propagation.**

Baryshev Alexander 1,2, Kazuhiro Nishimura 1, Tsuyoshi Kodama 1, Hiroyasu Uchida 1 and Mitsuteru Inoue 3,4; 1Toyoohashi University of Technology, Toyohashi, Aichi, Japan; 2CREST, Japan Science and Technology Corporation, Tokyo, Japan; 3Moscow State University, Moscow, Russian Federation.

In the past decade, there has been great deal of interest in photonic crystals (PCs) in which the dielectric constituents are periodically arranged [1]. These crystals have many interesting properties as far as basic physics is concerned but also in relation to technological applications. Apparently, possibility to tune such properties of PCs like band structure or dispersion by some external influences may enhance significantly applicability of PCs for applications. Especially for weak magnetic activity, width of new opened full band gaps will be vanishing. Found, that for Faraday geometry despite weak character of magnetic activity, strong sensitivity of dispersion for electromagnetic modes near band edges appears. This effect, obviously, can essentially increase importance of PCs for applications owing to possibility to tune dispersion of PCs by external magnetic field. It is very important especially for such devices like super-lenses and super-prisms that have in their basis the PC’s structure.


3:30 PM J2.12

**Superprism effect in magnetophotonic crystals.**

Alexey Petrovich Vinogradov 1, Alexander Mikhailovich Merlikin 2, Alexander Borisovich Granovsky 2, Mitsuteru Inoue 3,4 and Alexey Vinogradov 2, 1TITEI OIST Russian Academy of Sciences, Moscow, Russian Federation; 2Faculty of Physics, Lomonosov Moscow State University, Moscow, Russian Federation; 3Department of Electrical and Electronic Engineering, Toyohashi University of Technology, Toyohashi, Japan; 4CREST, Japan Science and Technology Agency, Saitama, Japan.

Photonic crystals have attracted wide and sustained interest in the past few years, in particular due to an opportunity to control of light propagation on the wavelength scale. The one-dimensional photonic crystals have been using in practice as periodic multiphase dielectric mirrors, but two-dimensional and three-dimensional photonic crystals have only recently been widely adopted. Their unique dispersion properties allow to control light collected by devices of super-small scales [1]. A superprism is a representative example of such devices [2]. The superprism effect consists in considerable deviation of a light beam caused by small changes of system parameters, like angle of incidence or frequency. Additional attractive features of PC appear as a result of magnetooptical materials. These new advantages consist not only in increase of magnetooptical effects [3, 4] (the Faraday and Kerr effects for example) but also in opportunity to control the PC properties by external magnetic field. In this communication we present model calculations of photonic band structure for 2D PC built up of magnetooptical matrix with square holes to study for the first time the magnetic superprism of an effect. We employ a simple square lattice model and restrict ourselves to less case. It is shown that an external magnetic field applied perpendicularly to the holes changes significantly 2D PC band structure and thus propagation of light through the PC. The effect exists even for a weak magnetooptical activity of the matrix but only for the definite set of model parameters. Thus, it makes possible to deflect a light beam by applying magnetic field without variation of frequency or initial angle of incidence. Besides, it is possible into control super-prism [2] by magnetic field. 1. J. D. Joannopoulos, P. R. Villeneuve and S. Fan // Nature 386, 143, (1997) 2. T. Baba, M. Nishimura // IEEE J. of Quant. Electr. 38, 909, (2002) 3. M. Inoue, K. Fujii, V. Abe, J. Appl. Phys. 85, 5768, (1999) 4. A. P. Vinogradov, A. M. Merlikin, A. B. Granovsky, M. Inoue // Journal of Communication Technology and Electronics 49, 88, (2004)

8:15 AM *J3.1*

**Three-Dimensional Magnetooptical Recording.**

Akiyoshi Itoh, Alexander Borisovich Granovsky 2, Kazuhiro Nishimura 1, Tsuyoshi Kodama 1, Hiroyasu Uchida 1 and Mitsuteru Inoue 3,4; 1Toyoohashi University of Technology, Toyohashi, Aichi, Japan; 2CREST, Japan Science and Technology Corporation, Tokyo, Japan.

Magnetophotonic crystals (MPCs) [1], composite materials in which magnetic materials are implanted into the dielectric lattice, have attracted major interest, because the control of the electromagnetic wave by MPC structure is expected to be a key technology for future applications in optoelectronics. Three-dimensional MPCs are of interest because they give a possibility for three-dimensional light control. Due to their magnetic properties the Faraday and magnetooptical Kerr effects in magnetic field are expected to be much stronger, therefore three-dimensional MPCs could be much more effective than existing devices. Today, there are a few kinds of three-dimensional photonic crystals which can be used for preparation of MPCs: synthetic opals, inverted opals and colloidal crystals. In present work we utilized high-quality opal photonic crystals [2] for the visible as a matrix for impregnating with magnetic material.

Crystalline structure of opal sample has continuous net of voids those were filled by magnetic material. Opal-ferite spindal and opal-vitram three-dimensional MPCs for the visible spectral region were prepared using a fabrication procedure developed. We studied an influence of concentration of reactants and temperature conditions (in the case of garnets) on magnetic properties of MPCs. Investigation of these samples by SEM, X-ray diffraction analyses and vibrating sample magnetometer shows that magnetic materials are synthesized in voids of opal matrices and obtained composites have typical magnetic properties. Since the photonic band structure is of fundamental interest, we investigated an influence of quantity of magnetic materials inside of opal samples on optical properties of MPCs synthesized. It was shown that the Faraday rotation outside the stop gaps has the behavior of magnetic component. We found the considerable changes of the Faraday rotation angle in photonic band gap of MPCs in comparison to bulk magnetic material implanted. [1] M. Inoue and T. Fujii, J. Appl. Phys. 81, 8 (1997). M. Inoue, K. I. Akune, T. Fujii, and M. Abe, J. Appl. Phys. 85, 8 (1999). [2] A. V. Baryshev, A. V. Anulevich, A. A. Kaplyanskiy, A. V. Kosobukin, M. F. Limonov, K. B. Samusev, and D. E. Usvyat, Physics of the Solid State 44, p. 1648 (2002).
reading layer located at the far side of the incoming optical beam becomes smaller due to the penetration of the light through the other layers, so another configuration is necessary. Double-MAMMOS scheme consists of 2-recording layers of differing compensation temperature (Tcomp) and one readout layer was proposed and discussed. For low reading power, the films are at T1 which corresponds to the compensation temperature of the 2nd recording layer. The magnetic field assistance is dependent on two factors: temperature T2 the 1st recording layer does not yield any stray field, so the information is copied from the 2nd layer to the read out layer. We can then choose the recording layer where information is read by changing the read optical power. This scheme is also not affected by the stray field effect of the compensation layer. It can be expressed by half size of focused laser spot. However, in the case of Magneto-Optical (MO) disk, magnetization in the 1st recording layer is not equal to zero, so the magnetic field assistance is dependent on two factors: temperature T2 the 1st recording layer does not yield any stray field, so the information is copied from the 2nd layer to the read out layer. If a certain level below the recording layer by the yielded stray field. Conversely, for high reading power, at the temperature (Tcomp) of the 2nd recording layer, where the 2nd layer becomes smaller due to the penetration of the light through the other layer, 15um over coat is covered. Read/Write testing was performed from the covered layer side. Therefore, both side recording can be accepted. The Write/Read tester has a blue laser diode of 405nm wavelength with high aperture objective lens. Resolution band width is 30Hz. In the case of conventional disk, CNR value of longer mark of 400nm as same as laser spot size shows large enough for practical use. However, the CNR of 200nm is small value for actual signal processing because it is beyond the optical resolution limit. On the other hands, in the case of ZF MAMMOS, even if recording mark length is 60nm. It is much shorter than the optical resolution limit of 200nm, the large CNR value can be kept. The areal density (Track width : 0.18um, Bit length : 60nm) becomes 60Gb/in2. Thus, it is found that write/read characteristic of ZF MAMMOS is very attractive for high density recording. Also, using improved recording material with minimizing domain reversal unit, rather shorter mark less than 60nm would be reproduced with large CNR value. This indicates that MO has a potential as a removable hard disk.

The speed limits for thermomagnetic writing are of critical importance for magneto-optical recording, which has become one of the most important technologies for removable storage media. In particular, the speed of the thermally assisted copying within magnetically amplified magneto-optical systems (MAMMOS) is of high technological interest [1]. Conventional pure magnetic recording schemes have a serious and unavoidable problem known as the ferromagnetic resonance (FMR) limit. Nevertheless, laser pulse writing was shown to lead to a potentially much faster process of magnetization reversal, of the order of a few picoseconds [2,3]. These experiments demonstrated the intrinsic capability of ultrafast high-speed rewritable storage under the thermomagnetic scheme. Here we present results of time-resolved study of ultrafast magnetic response of Gd23.1Fe76.9Co5 Mo MAMMOS structures under near actual read temperature condition (423 K). By an optical-pump and probe method we demonstrated that the photo-excitation could effectively excite coherent spin waves in the magnetic material. An intense (pump) optical beam excites the medium due to an ultrafast heating. A less intense (probe) beam monitors this photo-excited state through the magneto-optical Kerr effect. Time-domain measurements on the continuously excited precessional wave, the amplitudes of which decay, are used to determine the precession frequency. Mean magnetic field modulation (MFM) and reproduced by domain wall displacement detection (DWDD). A technique which can attain a recording density of 15 Gbit/inch2 (80 nm/bit, 540 nm/track) with the existing optical parameters of DVD has already been developed, in which the signals are recorded by magnetic field modulation (MFM) and reproduced by domain wall displacement detection (DWDD). If this technique could be employed in a DVD, a capacity of more than 20 GB per layer would be achieved. However, in order to perform such high-density recording, it has so far been necessary to place a magnetic field modulation head close to the recording film. This has made it difficult to apply the reproduction technology to a DVD type optical disk, which has a sandwiched-films structure, or to a Blu-ray type disk system, which has a layered head placed on the film side of the disk. In order to overcome this difficulty, we proposed a new recording method named Domain Tail Erasing (DTE), with which minute marks much smaller than a spot size can be written by light intensity modulation, as can be done with MFM. This new recording method enables high-density recording far beyond the optical resolution limit with a medium combining the layer structure of DWDD with that of light intensity modulation direct overwrite (LIMDOW). A recording performance nearly identical to that using MFM was confirmed with this method, using conventional optics with a wavelength of 660 nm and NA of 0.60. However, the DTE method still requires a bias magnet, which remains a disadvantage in cases in which a thinner drive apparatus is required. Moreover, there are also magnetic fields generated by introducing a device to generate a magnetic field as a magnetic film included in the medium. In order to obtain a sufficiently strong bias field to perform recording with a bias layer introduced into the DTE, a stray field from a bias layer must be reduced. The stray field from the bias layer was studied by simulation. A stray field most effectively worked on the recording layer when the Curie temperature of the bias layer was designed at a certain level below the recording temperature. Furthermore, by replacing part of the bias layer with a bias assist layer, which had a higher Curie temperature and lower coercive force, an even stronger stray field was generated. According to the simulation, a non-bias DTE medium was designed and a sufficiently low jitter value and dropout rate were obtained when magnetization in the bias layer was at 40nm and a track pitch of 740 nm, using the same optical parameters as those of existing DVDs. 

Conventional magnetic recording drives with areal density beyond 1 Tb/in2 will be faced with the contradictory problems, superparamagnetic limit and head field limit. Although extremely high magnetic anisotropy (Ku) media are needed to maintain the thermal stability of the recording tiny bits, the media cannot be recorded by available heads. Thermally assisted magnetic recording,
or hybrid recording, is expected to solve the problems by employing a thermo-magnetic writing scheme, i.e., by using local heating to temporally reduce the high magnetic coercivity in a thermally short field. First feature of the hybrid recording is high resolution recording capability by sharp thermal gradient as well as applying head field gradient. When the focused laser is irradiated locally to the perpendicular recording medium in recording direction, the clear bit patterns could be recorded by applying the head fields, which were much smaller than the coercivity at room temperature. The second feature is pico-second order high-speed magnetization reversal. A reduce the medium coercivity below the writing field is observed in the Gd-Fe-Co perpendicular thin film, when a 100 femto-second laser is irradiated on the film. This switching speed is much faster than the ferromagnetic resonance frequency. This result suggests that the hybrid recording scheme will overcome the upper limit as well as the paramagnetic limit. Since the hybrid recording solve the head field problem, the hybrid recording medium will be able to use extremely high Ku materials, such as FePt and Co/Pt L10 ordered FePt materials, Co/Pt and Co/Pd multilayer thin films, and Tb-Fe-Co magneto optical recording medium, whose Ku values are more than 107 erg/cc. The bit transitions are determined by the heating profile of the media as well as the head field gradient. Therefore, tiny bit patterns will be probably recorded in the strong exchange coupling media. The hybrid recording media have huge alternative of not only high Ku materials but also the film structure.

10:45 AM 33.6 Pseudo-binary alloys and exchange springs - adjusting the properties of high anisotropy FePt films for media applications in thermally assisted magnetic recording.
Jan-Ulrich Thiele, San Jose Research Center, Hitachi Global Storage Technologies, San Jose, California.

Magnetic media using materials with high magneto-crystalline anisotropy, KU, combined with a thermal assist to overcome write field limitations have been proposed as a potential technology to extend the areal density of magnetic recording beyond current limitations. Here we present an overview of recent work on adapting the properties of materials based on the high-Ku materials but also the film structure.

3:10 PM 33.7 Femtosecond Laser Pulse Induced Magnetization Dynamics.
Julius Hohlfeld, Seagate Research, Pittsburgh, Pennsylvania.

The development of laser systems that emit ultra-short laser pulses with pulse energies up to several mJ/pulse opened the way to induce and study magnetization dynamics on a femtosecond time scale. In this talk I will focus on four different topics in this new area of femtosecond magnetism: 1) the ultra-fast breakdown (erasure) of the magnetization magnitude within a few 100fs after the optical excitation, 2) the precession of the magnetization vector that is induced by the ultra-fast laser pulse when the direction of the external field and the magnetization in thermal equilibrium enclose an angle different from \( \pi \), 3) the speed limit of thermomagnetic writing when the static external field points in the opposite direction as the initial magnetization direction, and 4) the new technique of ultra-fast laser pulse induced ferromagnetic order in materials that undergo an anti-ferromagnetic - to - ferromagnetic transition at elevated temperature. Acknowledgments This work was performed as part of the Information Storage Industry Consortium (INSIC) program in Heat Assisted Magnetic Recording (HAMR), with the support of the U. S. Department of Commerce, National Institute of Standards and Technology, Advanced Technology Program, Cooperative Agreement Number 76NANB10096.


There has been an increasing interest for generating intense optical spots smaller than the diffraction limit of an objective lens. In addition to near-field imaging, intense sub-wavelength optical spots have potential applications in lithography and bio-chemical sensing. Near-field techniques that generate intense sub-wavelength nano-structures can obtain intense optical spots beyond the diffraction limit for optical data storage. The magnetic storage industry is also interested in sub-wavelength optical spots for heat assisted magnetic recording (HAMR) to overcome the superparamagnetic limit. HAMR is a potential technique to extend the physical limits of conventional magnetic recording. An optical spot is used to heat the recording medium to reduce its coercivity and enable recording by an external field. To achieve a density of 1 Tb per square inch, an optical spot diameter of 25 nm is required. A total dissipated power of 1-1 mW is required in the medium to enable recording data rates of 1 Gb/s. The ridge waveguide transmission (RWT) has been suggested as a near-field aperture for data storage. Various RWT designs have been investigated using electromagnetic modeling techniques, including finite difference time domain (FDTD) and finite element method (FEM). Models for a focused beam of light were integrated with the FEM and FDTD for more realistic scenarios. The focused spot size that can be obtained from a lens is proportional to the wavelength, and inversely proportional to the numerical aperture (NA) of the lens. Solid immersion lenses (SIL), in which the light is focused in a high refractive index solid, achieve smaller optical spots than the conventional diffraction limit of air-spaced objective lenses. Increasing the NA using a SIL increases the electric field at the focal region. Placing a near-field transducer in the proximity of such enhanced electric fields increases the near-field radiation from the transducer as well. Surface plasmon modes can be optically excited in a metal film using the Otto excitation technique in which light is incident on a high refractive index metal film and the metal film couples to the index dielectric spacer. Due to the total internal reflection at the high-index boundary, evanescent waves are created which couple efficiently into the surface plasmon modes over the metal film. By placing a low-index medium between the SIL and RWT a simple effect is obtained. We investigated the near-field optical system which is composed of a SIL, a RWT, and a thin low-dielectric index spacer in between. The RWT is optimized to yield a high transmission efficiency. This optical system provides a spot size of 31 nm and a maximum absorbed optical power density of 7.5x10^4 mW/nm. For a bit-aspect ratio of 1, these numbers are close to the range required by HAMR to achieve 1 Tb per square inch. With a higher bit-aspect ratio and a better focusing scheme, the design yields a much higher areal density.

SESSION J4: Optical Isolators
Chair: Koji Ando and Miguel Levy Wednesday Afternoon, December 1, 2004 Berkeley (Sheraton)

1:30 PM 34.1 Temperature Dependence Free Magneto-Optical (Tb,Bi)Fe Garnet Films Grown By LPE Method. Nobuo Imamura, Takashi Fukuhara, Yasuhiro Kuwano and Kenichi Shiroki; Opto Laboratory, Namiki Precision Jewel Co., Ltd., Tokyo, Japan; Research & Development, Dai-Ichi Kiden Co., Ltd, Chiofu-city, Tokyo, Japan.

Bi-substituted Tb-Fe Garnet Films grown by Liquid-Phase
Epitaxial (LPE) method are demonstrated as candidate temperature dependence free Faraday Rotators in the telecom devices or optical sensors applications. A bulk garnet with Tb:BiFeO3 and BiFeO3:LiF0.5SrF0.5 show opposite sign in temperature characteristics of the Faraday Rotation, ∆FR and the combined solid solution of (Tb,Bi)FeO3 is theoretically expected to become the temperature dependence free magneto-optical garnet crystal by controlling the composition x in the chemical formula Tb(3-x)BiFeO3. In experimental, the bulk garnet crystal, Tb:5BiO:4Fe:5SrO is grown by a flux method, with almost zero temperature dependence at 1310nm, was reported by T. TAMAKI. From the cost oriented industrial point of view, the LPE grown method should be desirable to make the temperature dependence free garnet material in the actual applications such as optical isolators or sensors. For the LPE grown method, lattice constants of the substrate are 12.46 and 12.50Å. Thickness of the tested garnet films are 131 to 386Å, and the ∆FR and temperature dependences are measured with a stabilized laser source at 1310nm. Temperature coefficients (TC) of the ∆FR are estimated using following relation, ∆FR/TC, where ∆FR shows difference of the FR angles in the temperature range between -10 and +80°C. As reported by TAMAKI, at x=0.48 to 0.56 in the Tb(3-x)BiFeO3, a couple of very low temperature dependence free garnet films are fabricated on a lattice constant of 12.46Å SGGA substrates through the LPE-Grown processing with optimized flux compositions. Thicknesses of the films are 232 to 322Å, and the ∆FR is 13 to 15deg. From -0.0024 to +0.0012deg/°C are measured at the TC=1310nm. These garnet films are well suited for the waveguides, but their temperature dependences less than one tenth compared to the conventional Faraday rotators in the telecom devices. [1] T. TAMAKI: Doctoral thesis, Tokyo Institute of Technology 1993


In optical applications, especially in optical communication, protecting light sources from harmful reflected energy is very important. With magneto-optic isolators, these light sources can be protected to extend their lifetime and performance by blocking back-reflected light. The active element in these optical isolators is a magneto-optic garnet. However, garnet is difficult to integrate with semiconductors due to the high thermal budget usually required to obtain the garnet crystal structure. For example, current isolator garnets cannot be integrated monolithically into a photonic integrated circuit due to the growth process, liquid phase epitaxy, which requires growth temperatures of >900 °C and also garnet substrates. In this work, magneto-optic garnets were grown monolithically by low-temperature reactive RF sputtering, followed by a ultra-short (<15 sec) annealing. The reactive ion etching (RIE) was applied for monitoring and controlling garnet growth thickness. For the measurement of the thickness, Fourier transform infrared (FTIR) spectroscopy. These garnets were grown onto several single and multilayered buffer layers, including yttrium oxide, which gave the best results. This buffer had an index of 1.9 and was more similar in thermal expansion to YIG than the other buffer layers. Various rib waveguides were fabricated with both wet-etching and reactive ion etching (RIE). The width of the waveguides varied from 2 to 12 μm and the height were varied from 0.5 to 1.0 μm. Sm-Co thin films were used for the biasing magnets. They were deposited on top of layers of Si3N4 and yttrium oxide, all using the same sputtering system that was used to deposit the garnet films. These magnetic films had high enough remanent fields to saturate the garnet films. Consequently, as they had coercivities of 1300 Oe, Faraday rotations and waveguide losses of the subsequent isolators were measured using laser wavelengths of 0.632, 1.33 and 1.55μm.

2:00 PM 14.3 Waveguide Optical Isolators Fabricated by Wafer Bonding, Tetsuya Mizumoto1 and Hideo Yokoi2, 1Dept. of Electrical and Electronic Engineering, Tokyo Institute of Technology, Tokyo, Japan; 2Dept. of Electronic Engineering, Shibaura Institute of Technology, Tokyo, Japan.

Optical isolators are indispensable to protect optical active devices from back-reflected light. The waveguide version of isolator is desired for an application to photonic integrated circuits. Also, the waveguide isolator is expected to contribute to the cost reduction of devices. To integrate an isolator with a semiconductor device, it is a critical issue to integrate a magneto-optic garnet crystal with high coupling efficiency. We developed wafer bonding technique to accomplish this and demonstrated an isolator operation in the interferometric isolator that is composed of a GaAsP guiding layer and employs a nonreciprocal phase shift. Also, we achieved a waveguide Tb:BiFeO3 and BiFeO3:LiF0.5SrF0.5 to construct a semileaky waveguide isolator, which has the great advantages of relaxed fabrication tolerance and wide operating wavelength range. In this presentation, the wave bonding of garnet with Hf:YIG and Cex:YIG is discussed including the surface treatment for hydrophilic bonding as well as the surface activation bonding in a vacuum chamber. For the hydrophobic bonding, it is essential to make the wafer surfaces hydrophilic prior to bond formation. We examined the application to optical fiber communication. In a preliminary experiment, an isolation of 5dB was obtained in the interferometric isolator composed of a GaAsP guiding layer, on which Cex:YIG was directly bonded as an upper cladding layer. In the semileaky isolator, LiFeO3 is bonded on a Cex:YIG guiding layer. In this waveguide, the electromagnetic field of TE modes are confined in the guiding layer, while TM modes are radiated into a LiFeO3 cladding layer. A unidirectional mode conversion is provided by the anisotropy of LiFeO3 and the Faraday rotation of Co-YIG. We obtained an isolation of 7.2dB/cm at 1550nm wavelength in a fabricated semileaky isolator. Further studies toward the improvement of isolation characteristics will be addressed for both types of waveguide isolators.

2:30 PM 14.4 Environments Towards the Realization of a Monolithically-Integrated Optical Isolator Incorporating Quasi-Phase Matched Magneto-Optical Effects, Barry Holmes, David C. Hutchings and Joseph J. Bregenzer, E/O (Optoelectronics), The University of Glasgow, Glasgow, United Kingdom.

When coupling laser diodes to optical waveguides, fibres or components, the inevitable back reflections that arise from the connection interface propagate into the laser cavity, resulting in what is known as feedback or injection noise [1]. This creates instabilities, restrictions on the operational speed of the devices and also reduced lifetime. Currently, in order to prevent these back reflections, bulk optical isolators have to be inserted into the laserwaveguide/fibre assembly. This not only introduces additional complexity in the alignment of the components, but also leads to a reduction in performance through packaging and, therefore, an inevitable increase in costs. Consequently, the development of a monolithically-integrated laser-optical isolator is probably one of the most important goals in the ever-increasing integration of optical components and will result not only in a reduction of dimensions and costs, but also an increase in the functionality, lifetime, and speed of photonic devices. Recently, we reviewed various architectures and designs and proposed a planar device [2] consisting of a passive reciprocal mode converter (RMC), coupled to a nonreciprocal magneto-optic mode converter (NRMC). We report here upon the progress that we have made to date in reviewing each of these critical aspects. In particular, we have explored how GaAs-AlGaAs RMCs that have been fabricated by our group, using three separate but novel approaches, will be presented. Each method results in a one-stage dry etch process, thereby eliminating the requirement of realignment and remasking of the sample for each subsequent etch, as well as reducing fabrication errors that are inevitably introduced through the wet etch stage. This significantly reduces the complexity and time taken to produce such samples and facilitates a far greater degree of control over design tolerances and run-to-run repeatability. Also reported are the initial results from experiments toward the realization of the NRMC stage, in which we are utilizing the integrated Co-YIG cladding waveguide through the periodic reversal of the applied magnetic field. K. E. Stubaker and M. B. Small 1984 IEEE J. Quantum Electron. 20 472 D. C. Hutchings 2003 J. Appl. Phys. D 36 2223 J. S. El-Rayafey and D. Yevic 2003 J. Lightwave Technol. 21 1544 J. Z. Huang, R. Scarmozzino, G. Ngy, M. J. Steel, and R. M. Osgood, Jr 2000 IEEE Photon. Techno Lett. 12 317

3:15 PM 14.5 Cd1-x,Mn2xTe Magneto-Optical Waveguide for Monolithical Integration of Optical Isolator into Optoelectronics Circuits, Vidyom Zayate, Nanoelectronics Research Institute, AIST, Tsukuba, Ibaraki, Japan.
Optical isolator and circulator are essential components of optical information systems. Non-reciprocal effect of magneto-optical materials is used in these functions. In these magneto-optical devices with semiconductor optoelectronic devices, there has been some progress toward dichroic semiconductor optical isolators. Due to the large Faraday rotation, the change in wavelength range and it increase when wavelength approaches to the Cd$_{1-x}$Mn$_x$Te band gap. However, the TM/TE mode conversion ratio was only 0.1% [2]. To fabricate an integrated optical isolator, the magneto-optic mode conversion in waveguide should exceed 95%. We proposed to use graded-refractive-index layers to increase magneto-optical mode conversion in waveguide [3].

The isolation ratio was above 10 dB/cm under magnetic field 0.1 kGauss. The high isolation ratio, low optical loss, high figure-of-merit of the Fe layer brought about the nonreciprocal loss shift, the magnetization vector of the ferromagnetic metal-semiconductor isolator is aligned parallel to the magnetic field of the TE mode light. To make this alignment possible, the nonreciprocal loss is observed on one side of the waveguide, and the propagation direction is perpendicular to the plane. The device consisted of a semiconductor optical amplifier (SOA) and Fe thin film on one sidewall. The operation principle is as follows: in the TE mode, a nonreciprocal loss shift is brought about by the transverse Kerr effect near the interface between the Fe and the core (SOA) layers. The propagation loss for the forward traveling light is compensated by the optical gain of the current injected InGaAsP multiple quantum well active layer, whereas the propagation loss for the backward traveling light is reduced. Thus, the optical isolator operation is realized. In our simulation using the perturbation theory, the nonreciprocal loss shifts are up to 15.7 dB/mm, and predicted. The FePt thin film was grown by metal-organic vapor phase epitaxy, and the Fe thin films were deposited by electron-beam evaporator. We measured the amplified spontaneous emission (ASE) intensity under the magnetic field B=2kG. The device was 0.6 mm long and kept at 17°C, and the emitted light was resolved to TE and TM mode components. Here we define the nonreciprocal ASE ratio R as (\text{ASE(+)}/\text{ASE(-)}))/\text{ASE(0G.)}. R=23% was obtained for the TE mode at a current density of 14.3kA/cm$^2$. On the other hand, nonreciprocal ASE was not observed for TM mode. These results indicate that the Fe layer brought about the nonreciprocal loss shift for the TE mode in the fabricated device, which is promising for the semiconductor-waveguide-type optical isolator proposed above.

We propose the FePt thin film for high density recording media due to the large polar Kerr rotation angle at the short wavelength. To investigate the potential for high density recording by using magneto-optical effect, we fabricated the SiN$_4$/FePt/Si multilayer structure. We have fabricated the multilayer thin film by sputtering method. We kept the working pressure of 5x10$^{-3}$ torr. To obtain the various composition of FePt thin film, we used co-sputtering of Fe and Pt target individually controlling the applied power. The Al layer thickness is fixed at 500 nm for optical loss, and the thickness of Cladding layer is fixed for 405 nm wavelength measurement. The refractive index of SiN$_4$ is 1.78 measured by
ellipsometry, and the composition of FePt is analyzed by AES (Auger Electron Spectroscopy) and RBS (Rutherford Backscattering Spectroscopy) for the confirmation of AES analysis. The magnetic properties are obtained by AGM (Alternating Gradient Magnetometer) and Spectral Polar Kerr Measurement system. X-ray diffraction is employed for the structure identification. Kerr rotation angle and the ellipticity of FePt layer with thickness change also have been obtained by computer simulation. The thickness of FePt thin films are varied form 5 nm to 30 nm for the thickness effect investigation. According to the XRD patterns, the structure of the FePt thin films have (111) texture for the FePt thin films. The maximum Kerr rotation angle of 0.82 degree at 10 nm thick of Fe3Pt15. But the thickness of FePt increased up to 30 nm, the Kerr angle is slightly decreased to 0.62 degree. The Fe 3d bands and Pt 5d bands of larger spin-orbit coupling effect cause the variation of magnetic moments at the interfaces in the thinner film. This tendency is very similar and the calculated results relatively well supported the experimental data.

15.2 BiYIG Waveguides on Glass Substrates: Etching Conditions and Seed Layers Effects. Jean-Luc Deschanvres, Aude Bouchard

The development of the telecommunication network especially at the access level requires the production at a low cost of the different optical components, which are involved in the propagation, the modulation, the amplification of the light. One of these optical components is the optical isolator, which protect the light sources from backreflected light. Current components are bulky and expensive and are based on the use of the high magneto-optic effect of the bismuth substituted yttrium iron garnets. Garnets are traditionally grown by liquid phase epitaxy (LPE) at high temperatures on monocrystalline sapphire wafers. In order to produce cheaper components we proposed to elaborate the garnet films on glass substrates with an aeroseal MOCVD process. The deposition process is based on a pyrolysis of an ultrasonic generated aerosol, which contained dissolved organometallic precursors. As source solution yttrium and iron acetylacetonates and bismuth triphenyl were dissolved in butanol at a concentration of 0.03Mol/l. Well adherent 0.5 μm thick films have been deposited in the temperature range 470°C - 530°C with deposition rates between 0.1 and 0.4μm/h. The composition of the deposited films depended on the deposition conditions (substrate temperature, aerosol flow, composition of the source solution). The as deposited films were amorphous and very smooth. Polycrystalline films were obtained by post annealing treatments during few hours at temperatures between 600°C and 650°C. The films with a composition closed to the stoichiometric value exhibited a pure non-textured polycrystalline garnet structure. By using a classical photolithography process combined with a wet chemical etch process with diluted solution of orthophosphoric or chloric acid, ridges with width ranging from 3 to 40 μm have been obtained. For the as deposited films, etch rate was more than one order of magnitude higher than for annealed films and it depended also on the Bi content. The annealing step was crucial because cracks appeared due to the thermal expansion mismatch between the garnet film and the glass substrate. Films have been tested as waveguiding layer of glass substrates. One with a high annealing point but a low thermal expansion and the other with a lower annealing point but with a thermal expansion well matched to the garnet film. More over In order to reduce the stress induced by the annealing, we performed the etching before the annealing. Despite of this fact, cracks appeared in the ridges during annealing for the first type of glass. For the second one because of the lower annealing temperature (600°C), the crystallization was not homogeneous. In order to improve the crystallization process we have used as seed layer a thin film of Y2O3. With this structure we have obtained uniform crystallized ridges which exhibited enhanced propagation properties of the light at 1.53 μm.

15.3 Magnetorefractive Effect in Magnetophotonic Crystals. Sergey Gennad'evich Erkovich1, Yulia Viktorovna Borkina1, Alexander Borovkov Graniokoy1, Alexei Petrovich Vinogradov2 and Mitsutomo Inoue1

Photonic crystals made from magnetic materials, known also as magnetophotonic crystals (MPCs), exhibit remarkable magnetooptical properties accompanied by two orders of magnitude enhancement in their Faraday and Kerr rotation [1,2]. The unique properties arise from the localization of light as a result of multiple interference of light within MPC. Besides traditional magneto-optical effects connected with spin-orbit interaction, a new magneto-optical effect in magnetic materials with large magnetoresistance, so-called magnetorefractive effect (MRE), was discovered and studied thoroughly (see [3] and references therein). The effects are attributed to considerable changes in the dielectric function, and therefore in optical properties, of systems with large magnetoresistance when they are magnetized. The usage of magnetic materials with large MRE as component materials of MPCs also has provided us with a new way to fabricate tunable by magnetic field optical devices. Magnetic nanogranular alloys "ferromagnetic metal-insulator" with tunnel-type magnetoresistance, for example Co-(Al-O) with metallic volume fraction close to the percolation threshold, are promising prospective components of MPCs because they exhibit large MRE, more than 1%, and are partly transparent in a wide spectral range [3].

We present results on theoretical investigation of optical properties of multicomponent MPCs. We have calculated the dependence of the thickness of magnetic layer on the magnetic field, using the ANMOS (Alternating Gradient Magnetometer) as the magnitude of the magnetic field. The calculation is based on the magnetization in the dependance of the thickness of magnetic layer on the magnetic field, using the ANMOS (Alternating Gradient Magnetometer) as the magnitude of the magnetic field. The calculation is based on the magnetization in the dependence of the magnetoresistance on the magnetic field. The magnetoresistance is calculated using the magnetoresistance ratio, which is given by the ratio of the change in the resistance of the magnetic layer to the change in the resistance of the magnetic layer when its orientation is changed.

15.4 Fabrication of One-Dimensional Photonic Crystal Structures on (Yttrium Iron Garnet) BiYIG Films by Ion Beam Processing. Xinyou Huang1, Rong Li2, Haichun C. Yang2, Peter D. Moran2 and Miguel Levy1,2

The fabrication of multiple defects in the optical bandgap and of high finesse grating segments are advantageous to the production of flat top spectral response magnetic photonic crystals [1] and to the simultaneous optimization of Faraday rotation and transmission intensity in such crystals [2]. In this presentation we explore the formation of single and multi-defect one-dimensional photonic crystals by focused ion beam (FIB) patterning on Bi-substituted yttrium iron garnet (BiYIG) film waveguides. The FIB fabrication is done using a Ga-ion beam at a current of about 60 pA. Milling on the garnet films lasts for several minutes. Of particular interest to this investigation is the fabrication of high aspect ratio gratings in the garnet film for use on tunable gratings to produce tunable gratings. These gratings are one of the most promising magnetic photonic crystals [1]. A comparison with electron-beam patterning techniques will be presented. The BiYIG films are fabricated on Gd3Ga5O12 (GGG) (111) single crystal substrates by rf magnetron sputtering, using a conventional radio frequency magnetron sputtering system.

The fabrication of multiple defects in the optical bandgap and of high finesse grating segments are advantageous to the production of flat top spectral response magnetic photonic crystals [1] and to the simultaneous optimization of Faraday rotation and transmission intensity in such crystals [2]. In this presentation we explore the formation of single and multi-defect one-dimensional photonic crystals by focused ion beam (FIB) patterning on Bi-substituted yttrium iron garnet (BiYIG) film waveguides. The FIB fabrication is done using a Ga-ion beam at a current of about 60 pA. Milling on the garnet films lasts for several minutes. Of particular interest to this investigation is the fabrication of high aspect ratio gratings in the garnet film for use on tunable gratings. These gratings are one of the most promising magnetic photonic crystals [1]. A comparison with electron-beam patterning techniques will be presented. The BiYIG films are fabricated on Gd3Ga5O12 (GGG) (111) single crystal substrates by rf magnetron sputtering, using a conventional radio frequency magnetron sputtering system.

The fabrication of multiple defects in the optical bandgap and of high finesse grating segments are advantageous to the production of flat top spectral response magnetic photonic crystals [1] and to the simultaneous optimization of Faraday rotation and transmission intensity in such crystals [2]. In this presentation we explore the formation of single and multi-defect one-dimensional photonic crystals by focused ion beam (FIB) patterning on Bi-substituted yttrium iron garnet (BiYIG) film waveguides. The FIB fabrication is done using a Ga-ion beam at a current of about 60 pA. Milling on the garnet films lasts for several minutes. Of particular interest to this investigation is the fabrication of high aspect ratio gratings in the garnet film for use on tunable gratings. These gratings are one of the most promising magnetic photonic crystals [1]. A comparison with electron-beam patterning techniques will be presented. The BiYIG films are fabricated on Gd3Ga5O12 (GGG) (111) single crystal substrates by rf magnetron sputtering, using a conventional radio frequency magnetron sputtering system.

The fabrication of multiple defects in the optical bandgap and of high finesse grating segments are advantageous to the production of flat top spectral response magnetic photonic crystals [1] and to the simultaneous optimization of Faraday rotation and transmission intensity in such crystals [2]. In this presentation we explore the formation of single and multi-defect one-dimensional photonic crystals by focused ion beam (FIB) patterning on Bi-substituted yttrium iron garnet (BiYIG) film waveguides. The FIB fabrication is done using a Ga-ion beam at a current of about 60 pA. Milling on the garnet films lasts for several minutes. Of particular interest to this investigation is the fabrication of high aspect ratio gratings in the garnet film for use on tunable gratings. These gratings are one of the most promising magnetic photonic crystals [1]. A comparison with electron-beam patterning techniques will be presented. The BiYIG films are fabricated on Gd3Ga5O12 (GGG) (111) single crystal substrates by rf magnetron sputtering, using a conventional radio frequency magnetron sputtering system.

The fabrication of multiple defects in the optical bandgap and of high finesse grating segments are advantageous to the production of flat top spectral response magnetic photonic crystals [1] and to the simultaneous optimization of Faraday rotation and transmission intensity in such crystals [2]. In this presentation we explore the formation of single and multi-defect one-dimensional photonic crystals by focused ion beam (FIB) patterning on Bi-substituted yttrium iron garnet (BiYIG) film waveguides. The FIB fabrication is done using a Ga-ion beam at a current of about 60 pA. Milling on the garnet films lasts for several minutes. Of particular interest to this investigation is the fabrication of high aspect ratio gratings in the garnet film for use on tunable gratings. These gratings are one of the most promising magnetic photonic crystals [1]. A comparison with electron-beam patterning techniques will be presented. The BiYIG films are fabricated on Gd3Ga5O12 (GGG) (111) single crystal substrates by rf magnetron sputtering, using a conventional radio frequency magnetron sputtering system.
Manganese doped perovskites are materials promising for data storage, demonstrating optically and field induced memory effects. By the method of plane waves propagation in PhCs. For the calculation of transmittance, reflectance and MO effects in 1D case transfer matrix method was utilized [1]. Theoretical investigations of 2D- and 3D-PhCs have been performed on the basis of solving eigenvalues problem obtained from Maxwell equations. Magnetic part of the medium polarization has been considered as a perturbation and corresponding MO effects were calculated in the first order of perturbation theory [2]. Enhancement of the Faraday effect in 1D PhCs has been revealed for the first time by M. Inoue et al. [1]. Later it was shown theoretically that the optimal sets of magnetic and nonmagnetic layers in 1D PhCs, almost of the Faraday effect in 1D PhCs' has been revealed for the first time in the presence of external magnetic field, since the magnetization of magnetic components in these crystals follows the direction of applied field. Another possibility to control the optical (magneto-optical) properties of magnetic photonic materials is the change of temperature. Influence of temperature on the magnetic photonic crystal properties is two-fold. Firstly, the temperature variation, near the temperature for spin-reorientation transitions, leads possibly to a change of the magnetization direction in the magnetic photonic crystal. Secondly, above the temperature for order-disorder phase transition, the magnetic components in magnetic photonic crystals are transformed to the paramagnetic state and lose their magnetic properties. In the present communication, we report the results of theoretical investigation on how temperature affects the photonic band gap effects in magnetic photonic crystals. [1] I. L. Lyubchanskii, N. N. Didenkov, M. I. Lyubchanskii, E. A. Shapovalov, and T. Rasing, J. Phys.D: Appl. Phys. 36, R277 (2003).

15.6 Optical Properties of Magneto-Photonic Crystals. Vladimir Ignovich Belotelov1 and Anastoliy Konstantinovich Zvezdin2; 

1M.V. Lomonosov Moscow State University, Moscow, Russian Federation; 2Institute of General Physics, RAS, Moscow, Russian Federation.

Periodic dielectric media, or photonic crystals (PhC), are promising structures for controlling the propagation of electromagnetic radiation. With respect to PhC applications to optical devices, it is advantageous to apply external magnetic fields or use magnetic materials as the constituents of PhC. This can lead to some new interesting phenomena of magnetooptics. We have studied magnetooptical (MO) properties of PhCs composed of dielectric materials with magnetic properties. We implemented the investigation of the magnetic field influence on the electromagnetic waves propagation in PhCs. For the calculation of transmittance, reflectance and MO effects in 1D case transfer matrix method was utilized [1]. Theoretical investigations of 2D- and 3D-PhCs have been performed on the basis of solving eigenvalues problem obtained from Maxwell equations. Magnetic part of the medium polarization has been considered as a perturbation and corresponding MO effects were calculated in the first order of perturbation theory [2]. Enhancement of the Faraday effect in 1D PhCs has been revealed for the first time by M. Inoue et al. [1]. Later it was shown theoretically that for the optimal sets of magnetic and nonmagnetic layers in 1D PhCs, almost of the Faraday effect in 1D PhCs' has been revealed for the first time in the presence of external magnetic field, since the magnetization of magnetic components in these crystals follows the direction of applied field. Another possibility to control the optical (magneto-optical) properties of magnetic photonic materials is the change of temperature. Influence of temperature on the magnetic photonic crystal properties is two-fold. Firstly, the temperature variation, near the temperature for spin-reorientation transitions, leads possibly to a change of the magnetization direction in the magnetic photonic crystal. Secondly, above the temperature for order-disorder phase transition, the magnetic components in magnetic photonic crystals are transformed to the paramagnetic state and lose their magnetic properties. In the present communication, we report the results of theoretical investigation on how temperature affects the photonic band gap effects in magnetic photonic crystals. [1] I. L. Lyubchanskii, N. N. Didenkov, M. I. Lyubchanskii, E. A. Shapovalov, and T. Rasing, J. Phys.D: Appl. Phys. 36, R277 (2003).


Manganese doped perovskites are materials promising for data storage, demonstrating optically and field induced memory effects. Optical absorption, electric conductivity, and magnetic resonance of LaGaNxMn1-xO3 crystals have been studied for different temperatures and compositions. Electron energy structure and optical functions of LaGaNxMn1-xO3 are calculated by ab initio pseudopotential model within density functional theory using generalized gradient approximation. Theoretical results are discussed in comparison with the experimental optical absorption spectra for different alloy compositions. We determine the dependence of the Jahn-Teller (JT) distortion on the manganese concentration from the equilibrium total energy analyses, and discuss effects of Jahn-Teller distortion on magnetic and transport properties of materials with different concentration x.

15.8 Theory for the Magneto-Optic Spectra of Nanocomposite Materials Using Coupled Dipole Methods. Damon Allen Smith1,2, B. L. Scott1, Yurii V. Barnakov3, Shanta Watanabe4 and Kevin L. Stokes5; 1Physics, Dillard University, New Orleans, Louisiana; 2Advanced Materials Research Institute (AMRI), University of New Orleans, New Orleans, Louisiana; 3Physics, Dillard University, New Orleans, Louisiana.  

We present calculations of the magneto-optical (MO) response of composites which contain closely-spaced nanoparticles. The materials are modeled as collections of coupled dipoles using a new approach based on a discrete dipole approximation (DDA). This approximation allows for dipole-dipole interactions between the particles and is justified when the individual particle size is much smaller than the wavelength of incident radiation. Due to the presence of off-diagonal components in the dielectric tensor of magneto-optically active materials, a matrix transformation into a right-left circular coordinate system is performed. This allows for diagonalization of the dielectric tensor and subsequent calculations of the polarizations of individual nanoparticles. The optical cross-sections of nonmagnetic materials were calculated and verified against calculations made using the standard DDA algorithm, DDS2CAT. Qualitative agreement is found between our 1D model and a polymer/nanoparticle composite containing various volume fractions of included magnetic particle. It is surmised that our new model will allow for guidance in the fabrication of nanocomposite materials with tunable MO characteristics.

15.9 Effects of 1 MeV C+ Irradiation on the Magnetic Properties of Ni(60%)/CuSi(100). Sang-Won Shin1,2, Chungsam Whang3, Jong-Han Lee3, In-Hoon Cho2, Jenghan Song4, Teagun Kim2, Jung Man Lee5 and Kibong Lee6; 1Physics, Yonsei Univ., Seoul, South Korea; 2Institute of Physics, Yonsei Univ., Seoul, South Korea; 3Advanced Analysis Center, Korea Institute of Science and Technology, Seoul, South Korea; 5Physics, Pohang Univ. of Science and Technology, Pohang, South Korea.

The effects of 1 MeV C ion irradiation with various ion dose and flux on Ni(60%)/Cu/Si(100) have been studied. As an effective-molecular magnetic anisotropy (PMA). After ion irradiation, the magnetic and structural properties were analyzed by the magnetooptical Kerr effect (MOKE) and grazing incident diffraction (GID). 1 MeV C ion irradiation was performed into Ni/Cu thin film with various ion doses ranging from 1 up to 5 × 1015 ions/cm2. As increasing ion dose, the coercivity of Ni/Cu thin film decreased from 16 to 22.1 (9.5 × 1015 ions/cm2), this is due to the spin reorientation toward in-plane magnetization induced by an increasing ion dose. The evidence is that the magnetic anisotropy of Ni/Cu is closely related to the magnetoelastic anisotropy of strained Ni film due to the lattice mismatch with the Cu(011) layer. From the GID measurement, as increasing ion dose, the peak position of Ni moves gradually toward the bulk Ni(200) peak position and the half width of the Cu(200) peak is getting narrow. It implies the fact that the relaxation of the strain and grain growth induced by ion irradiation is a function of ion dose. In order to obtain a net magnetic effect, C+ irradiation with a dose of 1×1015/cm2 was carried out by varying ion flux (100, 380 nA/cm2). As increasing ion flux, the coercivity of Ni/Cu thin film decreased and spin orientation more rapidly changed from PMA to in-plane. It is concluded that ion dose and flux play an important role of modification of the magnetic properties of Ni/Cu thin film.
nanoparticles should be affected due to this locally-enhanced electromagnetic field. For this reason, we have investigated the synthesis of magnetooptical functional superparamagnetic magnetite (Fe3O4) - gold nanoparticles. The chemically synthesized 8-10 nm magnetite and 2-4 nm gold nanoparticles were linked with the organic molecule, mercaptopropanesulfonic acid (MUA). Due to bifunctionality of this organic linker, a chemical bridge is formed from the surface of the particles with carboxyl groups (COOH, in the case of magnetite) and with thiol groups (SH, in the case of gold) In order to investigate an influence of origin of bonds in binary nanocomposites on magnetic properties, test samples of single-phase and physically-mixed magnetite-gold colloids were studied as well. All samples were characterized by UV-visible optical absorption spectroscopy, X-ray Diffraction (XRD), Dynamic Light Scattering (DLS), Fourier Transform Infrared Spectroscopy (FTIR) and Transmission Electron Microscopy (TEM). Faraday rotation spectra were taken from samples placed on single TEM grid. This allows correlating features in the Faraday spectra with the morphology of the nanoparticles in a straightforward manner. It was observed that superparamagnetic magnetite nanoparticles. In contrast, unlinked particles show only a slight change in the intensity of IVC without any change of peak position. We suggest that the observed changes in Faraday rotation spectrum of chemically-linked binary nanoparticles are due to the modification of optical properties near the surface plasmon resonance frequency of the gold nanoparticles. SESSION J6: Magneto-Optical Sensors and Characterization Chair: William Challoner and Richard Gambino Thursday Morning, December 2, 2004 Berkeley (Sheraton)

9:00 AM *J6.1 Application of Magnetic Garnet Films for Magneto-optical Imaging of anisotropic Field Distributions. Horst Donnath, Carsten Holthaus and Alexei Yourevich Trifonov; Dpt. of Physics, University of Osnabrueck, Osnabrueck, Germany.

Rare-earth iron garnet films of high quality can be grown by liquid phase epitaxy on paramagnetic substrates of gadolinium galliumgarnet. Such films are currently used for imaging of the spatial distribution of magnetic fields. This application is based on the Faraday rotation which can strongly be enhanced by bismuth incorporation. If gray scale imaging is desired, one is bound to use in-plane magnetized films. The physical properties of the films can be controlled by the chemical composition, the growth conditions and the crystallographic orientation. The sensor properties like sensitivity, dynamic range, signal linearity and unambiguity must be optimized according to the application desired. These properties, however, are not independent of each other. In addition, they strongly depend on the optical wavelength. Thus, it is necessary to find compromises. The influence of Faraday rotation, Faraday ellipticity, optical absorption, magnetic anisotropies and film thickness on the performance of a magnetooptical sensor film is investigated based on the modeling of the photoresponse, a new optimization process is introduced. The process is experimentally verified and application examples are demonstrated. Furthermore, two methods are presented to enhance the sensitivity of magnetooptical sensors. Using specific crystallographic orientations, an easy plane of magnetization can be derived which is inclined with respect to the film plane. If the magnetization lies in this plane a very high sensitivity is achieved. The dependence on the crystallographic orientation of the easy plane on the growth direction is calculated and the sensitivity and dynamic range are derived. Experimental results of a [112] oriented garnet film are in agreement with calculations. Garnet films which are magnetized along the film normal due to a strong induced uniaxial anisotropy support magnetic domains. If the collapse field perpendicular to the film plane is small, such films can be used as very sensitive indicator films. Such films are easier to prepare than sensitive in-plane films. However, the spatial resolution is limited by the size of the domains. This disadvantage can be avoided by applying a bias field in the film plane. Directly at the in-plane collapse field the sensor film is in-plane magnetized yielding high spatial resolution at still high sensitivity. The splitting of magnetic anisotropy phases with in-plane induction is demonstrated. Experimental results are in agreement with calculations. Magneto-optical imaging becomes complicated, if the cubic anisotropy of the garnet films must be taken into account. This is the case for high-sensitive films. The influence of this anisotropy on the sensor performance depends on the crystallographic orientation. It is shown how this influence can be minimized.


Bismuth-doped rare earth iron garnets (Bi:RIG) are well known magnetooptical materials with large Faraday rotations in the visible and infrared. The Faraday rotation in bismuth doped garnets is essentially proportional to the bismuth concentration and so growth conditions must be optimized to maximize this dopant. Recently we have achieved high volumes in telecommunications applications such as isolators, circulators, interleavers, switches and variable optical attenuators. Materials for these devices have positive uniaxial anisotropy such that the film is easy magnetized parallel to the magnetic field. However interesting new devices can be enabled by negative uniaxial anisotropy. A better understanding of the requirements to achieve magnetooptical devices with negative uniaxial anisotropy is sought in this study. Growth of antiparallel magnetic anisotropy arises from ionic ordering on sites made non-equivalent by the growth direction. It can result from rare earth-rare earth pairs, bismuth-rare earth combinations and/or transition metal doping. Almost all growth-induced anisotropy studies have occurred on the easy growth, non-facet (111) direction and result in positive uniaxial anisotropy, Ku. In the demagnetized state, this results in serpentine stripe domains of alternating up and down orientation. When a bias field greater than the saturation magnetization is applied, the domains anti-parallel to the field collapse and the material becomes a saturated single domain such as is required for magnetooptic isolators. Negative growth-induced anisotropy has been seen in films containing praseodymium and neodymium, since these bismuth-based garnets have unique magnetic ordering opposite to the rest of the rare earths. But these ions also come with a host of complex magnetic properties including large damping to slow down device speeds and create additional non-uniform effects. Best planar device success has been achieved with (100) Bi:La:Fe:Ga:Y films on (100) gadolinium gallium garnet substrates. These have been used in magnetooptoelectric indicator applications in contact with magnetic domains and magnetic fluxes in materials including high temperature superconductors and magnetic tape. However, the growth conditions needed to produce negative uniaxial anisotropies involve high undercoolings resulting in poor process control. Therefore there has been a need to develop a more complete understanding of growth-induced anisotropy, particularly in orientations other than (111). The present study covers different combinations of rare earths and transition metals to yield negative anisotropy films with high Faraday rotations, tunable anisotropy, strong, uniform, reversible response to magnetic fields, high speed and reproducible properties. These films are expected to find new applications in magnetic field and current sensors and new telecommunications devices.
high-resolution Kerr microscopy. Using these samples as a magneto-optic layer, we obtained images of the intermediate state of type-I superconductivity in the bulk, an intermediate state that consists of an intricate pattern of superconducting and normal (flux bearing) domains. A disordered array of magnetic flux tubes is observed to move within the bulk. A typical pattern with a length scale of a few hundred nanometers was observed. This intermediate state was imaged using the same microscope and a variety of techniques, including cryo-EM. The intermediate state can be observed in the bulk of the sample, even at temperatures as low as 4 K. The intermediate state is a state in which the magnetic and superconducting order parameters are simultaneously present, and it is observed in a wide variety of magnetic superconductors.

**References**


**Abstract**

We present a detailed study of the intermediate state in a type-I superconductor. The intermediate state is a state in which the magnetic and superconducting order parameters are simultaneously present, and it is observed in a wide variety of magnetic superconductors. The intermediate state can be observed in the bulk of the sample, even at temperatures as low as 4 K. The intermediate state is a state in which the magnetic and superconducting order parameters are simultaneously present, and it is observed in a wide variety of magnetic superconductors.
Nonlinear magneto-optical Kerr effect in magnetization-induced second-harmonic generation (SHG) is a well recognized and an effective probe of magnetism in surfaces, interfaces and nanostructures. This sensitivity arises from a simultaneous breakdown of the structural and time-reversal symmetry, which occurs at surfaces and interfaces in the case of centrosymmetric materials. Second-order nonlinear magneto-optical Kerr effect (MOME) is of special interest, since it appears in magnetization-induced changes in the polarization, phase or the intensity of the SHG radiation can exceed the linear magneto-optical Kerr effect (MKE) by several orders of magnitude. Till then, the nonlinear magneto-optics was restricted to the second-order NOMEK, while third-order NOMEK was not studied. Nevertheless, magnetization induced third-harmonic generation (THG) appears to be a sensitive probe of magnetism in nanomaterials. In this paper, the results of the experimental observation of third-order NOMEK in magnetic thin films are presented. It is demonstrated that the third-order NOMEK parameters in thin films are comparable with that of the second-order NOMEK and exceed the MOMEK by an order of magnitude. The samples studied are thin films of Co and epitaxially grown Fe(110) of the thickness of 100-200 nm, Bi-doped yttrium iron-garnet films of 200 nm thick. The THG measurements were performed using YAG:Nd laser operating at 1064 nm wavelength and pulse duration of 20 ps. A saturating magnetic field of 0.5 kOe was applied by permanent magnets in the geometry of the transversal, longitudinal or polar Kerr effect. The magnetization induced phase shift of the third harmonic (TH) wave is observed, which stays in agreement with the phenomenological treatment of the magnetization-induced cubic susceptibility tensor. The rotation angles of the TH wave polarization up to 20 degrees were observed for Co films, which is the same order effect as the second-order NOMEK. For the transversal magnetic field application, odd in magnetization variations in the intensity and phase of the frequency-tripled light are observed. THG magnetic contrast in thin metal films is about 0.15 and for Bi-YIG is about 0.8. The largest magnetization-induced phase shift of 70 deg. is observed for Co films. Thus, the observed third-order NOMEK reveals giant enhancement. Large values of the third-order NOMEK are attributed to the role of the surfaces and interfaces in magnetization-induced THG.

SESSION J7: Magneto-Optical Materials II
Chair: Richard Gambino
Thursday Afternoon, December 2, 2004
Berkeley (Sheraton)

1:30 PM J7.1
Suitability of Fe-doped BaTiO3 for waveguide magneto-optic isolators. Ashok Rajamanickam1, David Bonot2, G. F. Dionne2, and Caroline A. Ross3. 1Department of Materials Science and Engineering, 2Department of Electrical Engineering, 3Department of Physics, Technology, and Research, Massachusetts Institute of Technology, Cambridge, Massachusetts; 4Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts.

This study investigates the suitability of Fe-doped BaTiO3 and other pervoskites as an optical isolator material that can be integrated as a waveguide onto a silicon based optoelectronic circuit. BaTiO3 pervoskite is chosen for this study because it is a transparent material that grows epitaxially on MgO. Three different compositions of Fe-doped BaTiO3 films were grown by pulsed laser deposition (PLD), using an excimer laser wavelength of 248 nm (KrF) at temperatures of 700 C and laser fluence of 20 J/cm2. The films were characterized by wavelength dispersive spectroscopy, x-ray diffraction, and magnetic and optical measurements. The films grow tetragonally with (001) face perpendicular to the polarization plane of TH wave in observed, which stays in agreement with the phenomenological treatment of the magnetization-induced cubic susceptibility tensor. The rotation angles of the TH wave polarization up to 20 degrees were observed for Co films, which is the same order effect as the second-order NOMEK. For the transversal magnetic field application, odd in magnetization variations in the intensity and phase of the frequency-tripled light are observed. THG magnetic contrast in thin metal films is about 0.15 and for Bi-YIG is about 0.8. The largest magnetization-induced phase shift of 70 deg. is observed for Co films. Thus, the observed third-order NOMEK reveals giant enhancement. Large values of the third-order NOMEK are attributed to the role of the surfaces and interfaces in magnetization-induced THG.

from 0.109 deg/um for Fe = 50 at% to 0.033 deg/um for Fe = 20 at%, while optical absorption decreases much faster. There is therefore an improvement in the magnetooptic figure of merit (ratio of third-harmonic generation to optical absorption) as the Fe content decreases from 50% to 20%. Other iron-based pervoskite systems have also been investigated, including orthoferrites of the formula AFe3O4. CeFe3O4, for example, shows a Fe-doped BaTiO3 ferrimagnet (NGME) in Fe of 0.5 at%.

Nonlinear magneto-optical Kerr effect in magnetization-induced second-harmonic generation (SHG) is a well recognized and an effective probe of magnetism in nanomaterials. In this paper, the results of the experimental observation of third-order NOMEK in magnetic thin films are presented. It is demonstrated that the third-order NOMEK parameters in thin films are comparable with that of the second-order NOMEK and exceed the MOMEK by an order of magnitude. The samples studied are thin films of Co and epitaxially grown Fe(110) of the thickness of 100-200 nm, Bi-doped yttrium iron-garnet films of 200 nm thick. The THG measurements were performed using YAG:Nd laser operating at 1064 nm wavelength and pulse duration of 20 ps. A saturating magnetic field of 0.5 kOe was applied by permanent magnets in the geometry of the transversal, longitudinal or polar Kerr effect. The magnetization induced phase shift of the third harmonic (TH) wave is observed, which stays in agreement with the phenomenological treatment of the magnetization-induced cubic susceptibility tensor. The rotation angles of the TH wave polarization up to 20 degrees were observed for Co films, which is the same order effect as the second-order NOMEK. For the transversal magnetic field application, odd in magnetization variations in the intensity and phase of the frequency-tripled light are observed. THG magnetic contrast in thin metal films is about 0.15 and for Bi-YIG is about 0.8. The largest magnetization-induced phase shift of 70 deg. is observed for Co films. Thus, the observed third-order NOMEK reveals giant enhancement. Large values of the third-order NOMEK are attributed to the role of the surfaces and interfaces in magnetization-induced THG.

1:45 PM J7.2

The effects of codoping of GaN:Mn films by silicon and magnesium is investigated. Three sets of samples; GaN:Mn, GaN:Mn:Si and GaN:Mn: Mg, are grown by metal organic chemical vapor deposition on sapphire under identical conditions, while dopants are injected into the gas phase during growth. The Mn concentration in all films is kept constant, and the dopant (silicon and magnesium) concentration is varied. Secondary ion mass spectroscopy (SIMS) confirmed that Mn concentration in the films does not change as dopants are added. Ferromagnetic properties of Bi- YIG is about 0.8. The largest magnetization-induced phase shift of 70 deg. is observed for Co films. Thus, the observed third-order NOMEK reveals giant enhancement. Large values of the third-order NOMEK are attributed to the role of the surfaces and interfaces in magnetization-induced THG.

The magnetization induced phase shift of the third harmonic (TH) wave is observed, which stays in agreement with the phenomenological treatment of the magnetization-induced cubic susceptibility tensor. The rotation angles of the TH wave polarization up to 20 degrees were observed for Co films, which is the same order effect as the second-order NOMEK. For the transversal magnetic field application, odd in magnetization variations in the intensity and phase of the frequency-tripled light are observed. THG magnetic contrast in thin metal films is about 0.15 and for Bi-YIG is about 0.8. The largest magnetization-induced phase shift of 70 deg. is observed for Co films. Thus, the observed third-order NOMEK reveals giant enhancement. Large values of the third-order NOMEK are attributed to the role of the surfaces and interfaces in magnetization-induced THG.

2:00 PM J7.3

This study investigated the suitability of Fe-doped BaTiO3 and other pervoskites as an optical isolator material that can be integrated as a waveguide onto a silicon based optoelectronic circuit. BaTiO3 pervoskite is chosen for this study because it is a transparent material that grows epitaxially on MgO. Three different compositions of Fe-doped BaTiO3 films with 20, 30 and 50% Fe substituted for Ti, were grown by pulsed laser deposition (PLD), using an excimer laser wavelength of 248 nm (KrF) at temperatures of 700 C and laser fluence of 20 J/cm2. The films were characterized by wavelength dispersive spectroscopy, x-ray diffraction, and magnetic and optical measurements. The films grow tetragonally with (001) face perpendicular to the polarization plane of TH wave in observed, which stays in agreement with the phenomenological treatment of the magnetization-induced cubic susceptibility tensor. The rotation angles of the TH wave polarization up to 20 degrees were observed for Co films, which is the same order effect as the second-order NOMEK. For the transversal magnetic field application, odd in magnetization variations in the intensity and phase of the frequency-tripled light are observed. THG magnetic contrast in thin metal films is about 0.15 and for Bi-YIG is about 0.8. The largest magnetization-induced phase shift of 70 deg. is observed for Co films. Thus, the observed third-order NOMEK reveals giant enhancement. Large values of the third-order NOMEK are attributed to the role of the surfaces and interfaces in magnetization-induced THG.

2:15 PM J7.4
Structural Analysis of Mn-doped ZnO Thin Films Deposited by RF Magnetron Sputtering. C. Lu1, F. Yun2, Pierre Ruterana2, Sang-Jun Cho3, B. Xiao2, and Hadis Morkoc; 1Dept. of Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia; 2SIFCOM UMR 6176 CNRS-ENSICAEN, 3Ecole Nationale Supérieure d'Ingénieurs de Caen, France.
There is not dearth of reports in the literature arguing in favor and also against Mn-doped ZnO being ferromagnetic with Curie temperatures exceeding room temperature. In this vein, we have deposited Mn-doped ZnO thin films by RF magnetron sputtering on c-plane sapphire substrates, and analyzed them. The magnetic properties of the Mn-doped ZnO films have been measured by a superconducting quantum interference device (SQUID) magnetometer. Clear hysteresis in magnetization vs. magnetic field was observed at room temperature. The magnetization measurements as function of temperature under zero-field-cooled and field-cooled conditions showed significant difference up to 300 K. High-resolution x-ray diffraction measurements revealed that the Mn-doped ZnO films possessed a single phase wurtzite structure without shift of ZnO (0002) peak position. Transmission electron microscopy analysis shows a columnar growth with small rotations around the [0001] axis of the wurtzite structure, with an average domain size of 50 nm. This columnar growth is disrupted during Mn-doping which leads to a ZnO film containing a high density of Mn related cubic and hexagonal precipitates. The origin of the ferromagnetic properties of the Mn-doped ZnO film will be discussed.

Magnetic Properties of Epitaxially Grown Zn1-xCoxO Thin Films. Feng Yun, Varatharajan Rengarajan, Jeff Nause and Hadis Morkoc. Virginia Commonwealth University, Richmond, Virginia; Cermet, Inc., Atlanta, Georgia.

Incorporation of magnetic impurities into a host semiconductor has been used for decades to obtain diluted magnetic semiconductor (DMS), driven by an interest in magnetoelectronics, and in particular the recent prospects of spintronics. This new class of materials finds potential applications in devices such as transistors, LEDs, memory elements, sensors and optical switches. Theoretical prediction of ferromagnetism above room temperature in transition metal doped ZnO has spurred the experimental efforts in this field. However, there are quite conflicting reports as to the presence of ferromagnetic behavior as well as the origin of such behavior. We have conducted a systematic approach of magnetic characterization using a series of Zn1-xCoxO samples with different cobalt composition. The Zn1-xCoxO thin films were epitaxially grown by metalorganic chemical vapor deposition (MOCVD) on quartz and ZnO substrates. The Co composition was adjusted by controlling the bubbler temperature and flow of carrier gas. Various magnetic measurements were performed using a Quantum Design MPMS system, which utilizes a superconducting quantum interference device (SQUID) magnetometer. Magnetic hysteresis curves were observed at 5K which persisted at 300K, characteristic of ferromagnetic behavior. Temperature dependent magnetization was recorded at both zero-field cooled (ZFC) and field cooled (FC) conditions. Changes of magnetization were observed under ZFC and FC conditions in some samples from 5K up to 300K. Composition-dependent changes in magnetization were also observed among samples with different cobalt doping, indicative of ferromagnetism related directly to cobalt incorporation. Discussion of the magnetic characteristics and their possible origin in our epitaxial Zn1-xCoxO layers will be presented as well as analysis using Curie-Weiss law and material parameters.