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Nano-engineered high-performance magneto-optic garnet materials

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Nano-engineered high-performance magneto-optic garnet materials

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OUTLINE

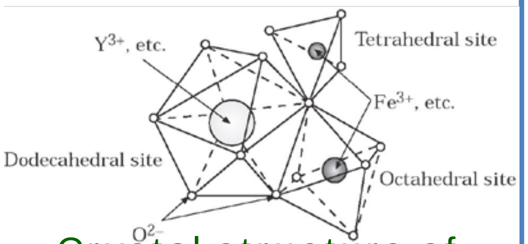
- **Introduction**
  - ✓ Introduction to Bismuth- and rare-earth-substituted iron garnets and application examples
- **Material synthesis and characterization**
  - **RF magnetron sputtering technology**
  - **Conventional oven annealing for crystallizing the amorphous layers**
- **Thin-film engineered garnet materials, properties & applications**
  - **$(Bi, Dy)_3(Fe, Ga)_5O_{12}$ and**
  - **$(Bi, Lu)_3(Fe, Al)_5O_{12}$**

Introduction to Rare Earth Iron garnets

Rare-earth iron garnets: $R_3Fe_5O_{12}$ where R is a rare earth atom

- **Commonly known garnet materials are:**

Yttrium Iron garnet (YIG = $Y_3Fe_5O_{12}$),
Gadolinium Gallium garnet (GGG= $Gd_3Ga_5O_{12}$) and
Bismuth Iron garnet (BIG = $Bi_3Fe_5O_{12}$)



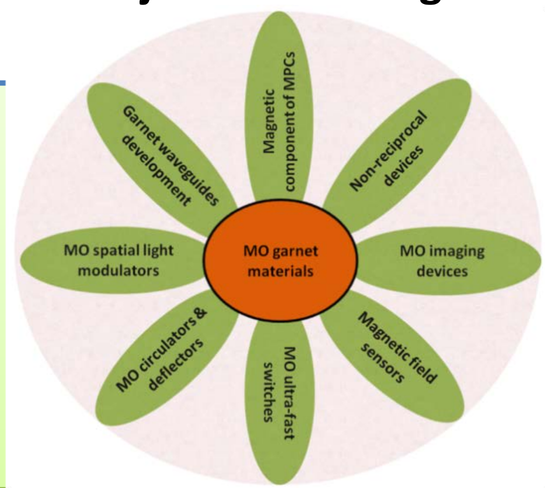
Crystal structure of magnetic garnets

- **The two very important subclasses of garnets for use in magneto-optic (MO) applications are described by:**

$(Bi, Dy)_3(Fe, Ga)_5O_{12}$ and $(Bi, Lu)_3(Fe, Al)_5O_{12}$

- Bismuth-substituted rare-earth iron garnets doped with Ga or Al, of importance due to the strong Faraday effect and a large variety of possible properties adjustable through material composition

- magnetic recording media
- magnetic field sensors
- MO imaging media
- MO planar waveguides
- magnetically-tunable photonic crystal structures



Background theory: Faraday effect

Magneto-optical phenomenon = interaction between light and magnetic field

$$\beta = V\,B\,d$$

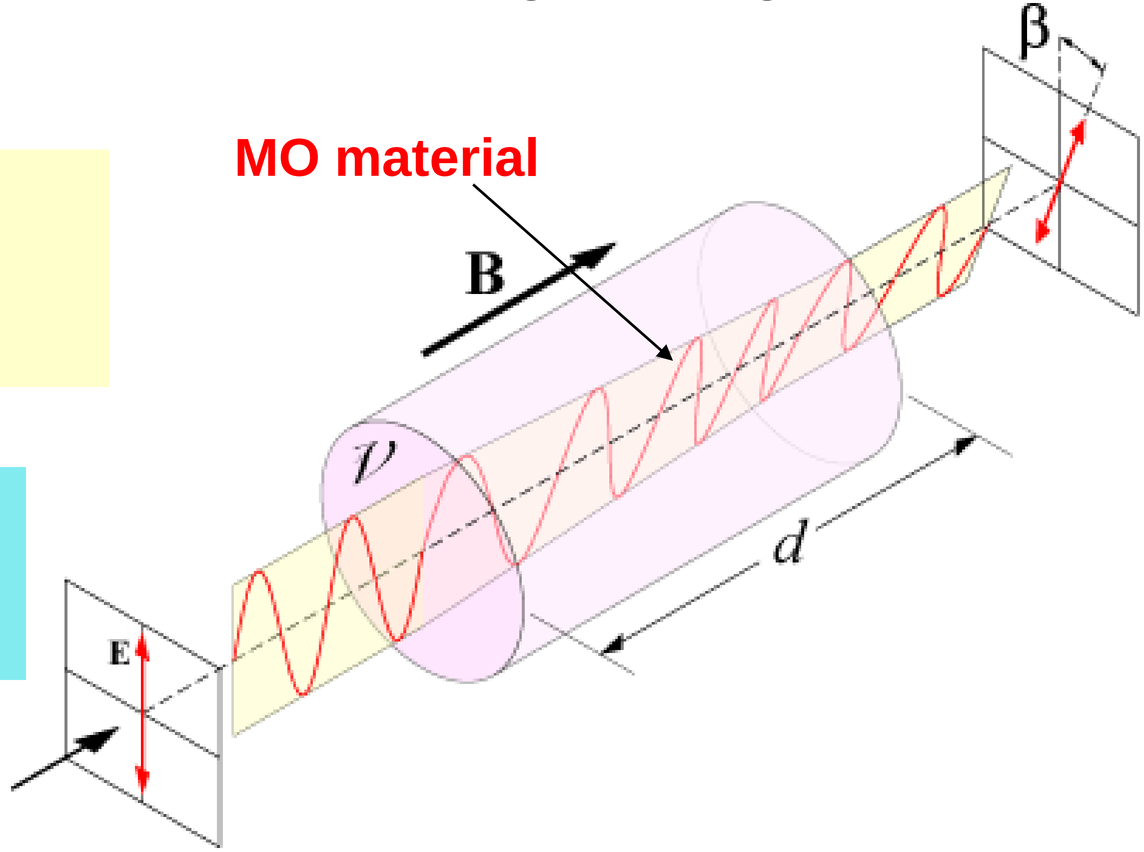
β = Faraday rotation angle

V = Verdet constant

d = material thickness

For thin-film materials, we use specific Faraday rotation:

θ_F [°/μm] = β / d (at $B = B_{sat}$)

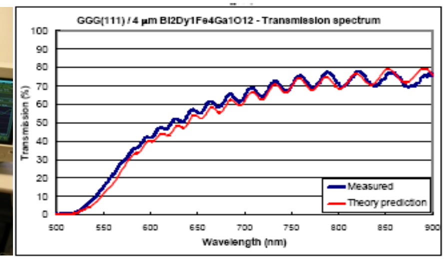


Extraordinary magneto-optical properties of Bi-substituted iron garnets first reported in 1969 (C. F. Buhrer, J. Appl. Phys. 40(11), 4500–4502, 1969).

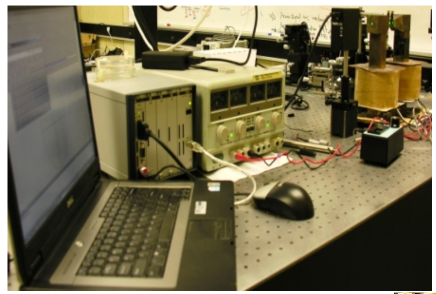
- **Highest specific Faraday rotation in the visible and near-IR regions (of all semi-transparent dielectric materials)**

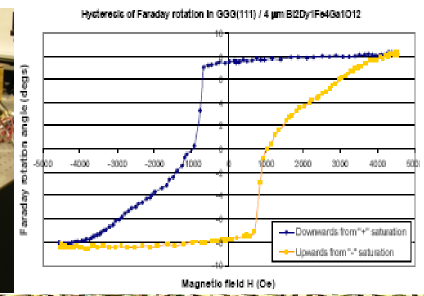
Thin film materials synthesis & characterization

RF Magnetron sputtering (a common method & very suitable for integrated-optics devices)
Our system at ESRI, ECU



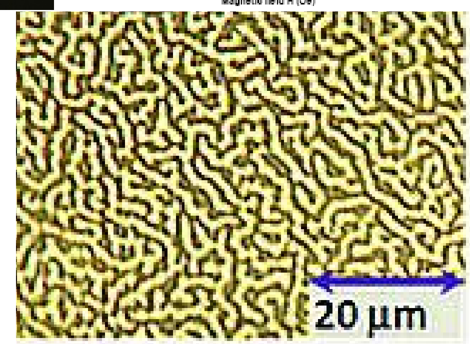
Optical characterization

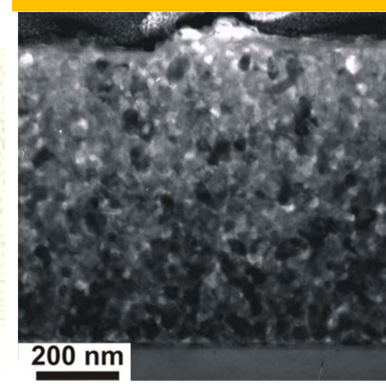




MO characterization

Magnetic and microstructural characterization





- **The parameters of importance are: film thickness, absorption spectra, specific Faraday rotation, coercive force, switching field, saturation field, and magnetization direction**
- **Optimization of magnetic properties is crucial for the development of new functional materials and for many emerging technologies in integrated optics and photonics**

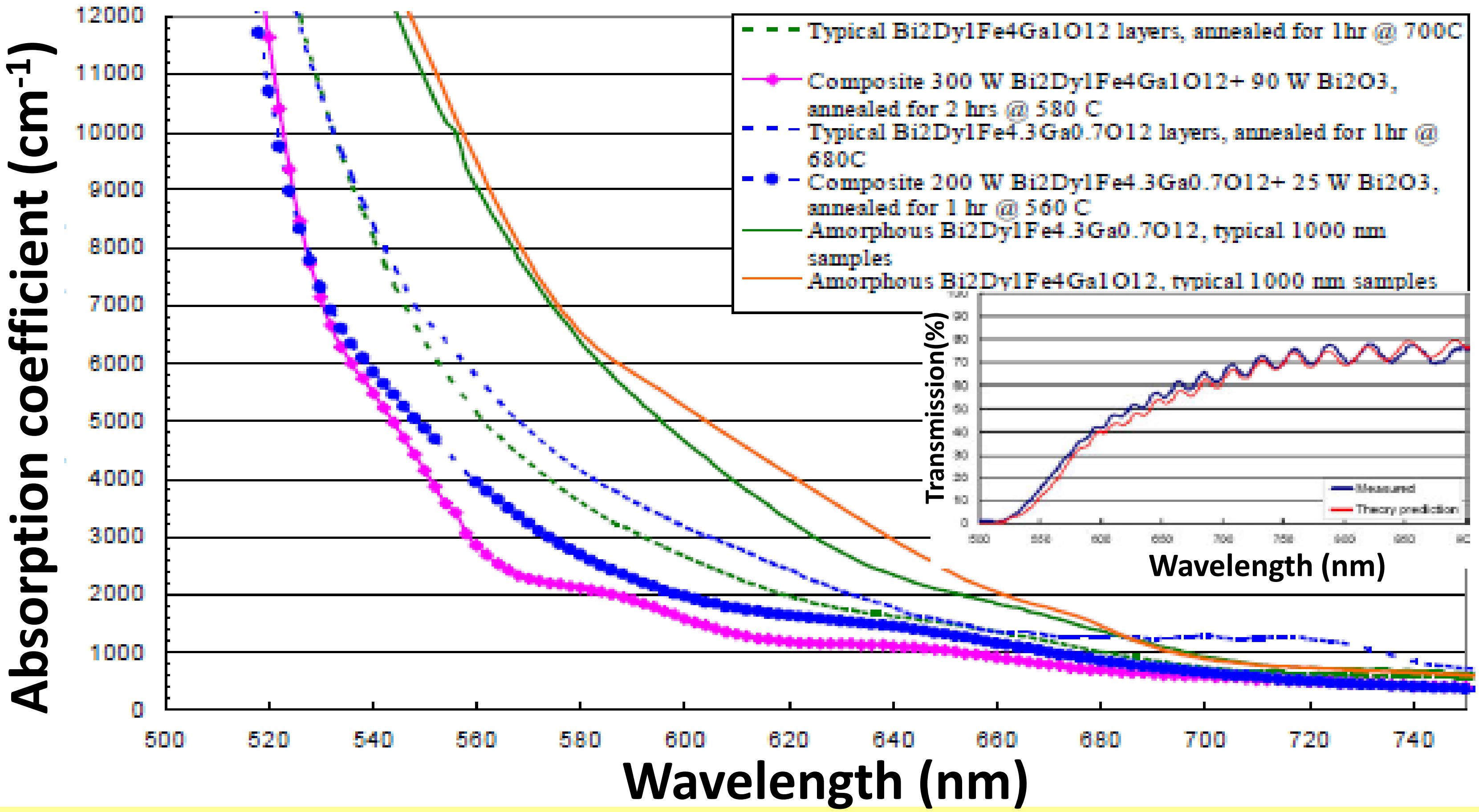
MO thin films & process parameters

Photographs of a correctly annealed garnet-Bi_2O_3 nanocomposite thin film and of two other nanocomposite films of similar type, but over-annealed

- **Amorphous films: High optical absorption + no magnetism ⇒ Zero Faraday rotation**
- **Crystallized films: Low optical loss + magnetization ⇒ High MO figures of merit are possible** $Q\,[°] = 2 * |\Theta_F|\,[°/\mu m] \,/\, \alpha\,[\mu m^{-1}]$

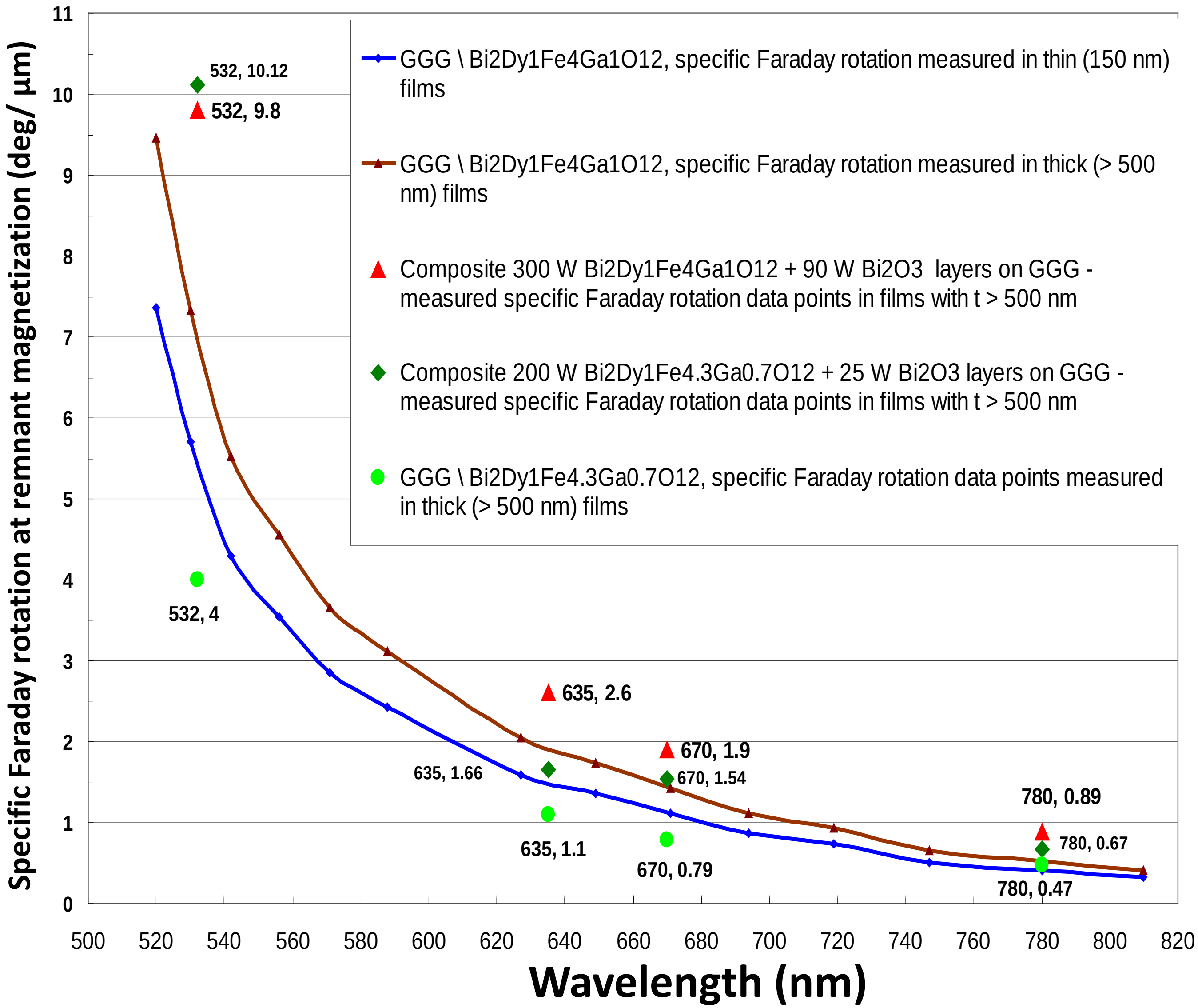
The optimized annealing regimes for highly Bi-substituted garnet materials are strongly dependent on the film composition

$Bi_2Dy_1Fe_{5-x}Ga_xO_{12}$: Bi_2O_3 thin film materials and engineering of their optical properties



- The parameters of importance are: absorption coefficient and specific Faraday rotation spectra. Co-deposition from a garnet-stoichiometric target + Bi_2O_3 target reduces absorption significantly (M. Vasiliev, M. N. Alam et al, Opt. Express 17(22), 19519–19535, 2009).
- Correctly annealed films with optimized Bi_2O_3 content also show increased Faraday rotation (M. Vasiliev, M. Nur-E-Alam, K. Alameh et al, J. Phys. D Appl. Phys. 44(7), 075002, 2011).

$Bi_2Dy_1Fe_{5-x}Ga_xO_{12}$: Bi_2O_3 thin film materials and their properties – Faraday rotation



Optical properties of garnet layers depend significantly on the material phase

Material's phase content depends on the process parameters

MO Figure of Merit,

$Q = 2 * |\Theta_F| / A$;

$\Theta_F = 0.1 – 10$ °/µm;

$A = 0.01 – (> 7000)\ cm^{-1}$

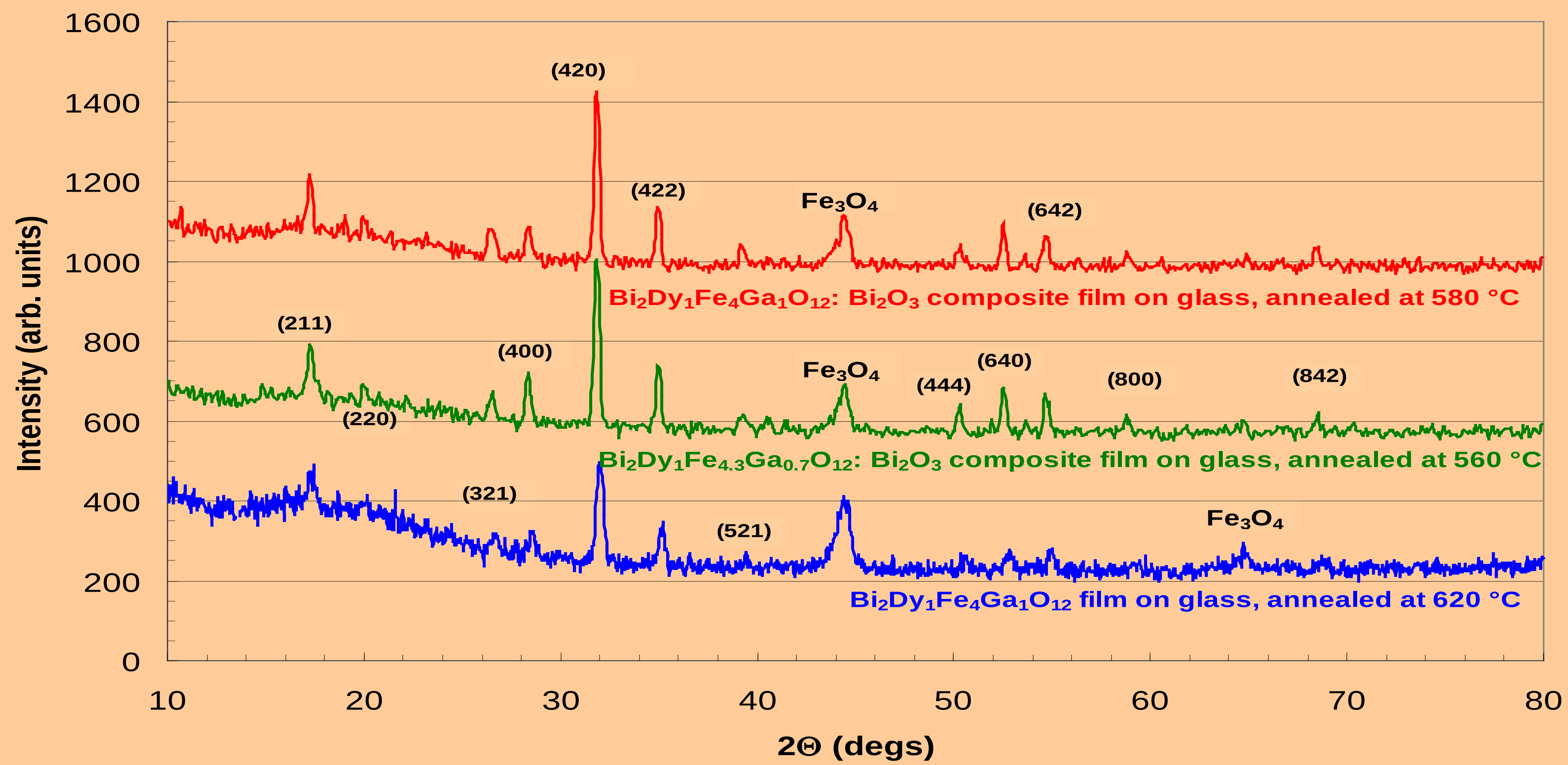
We achieved:

Q (green) ≈ 30°

Q (red) ≈ 50°

Q (1550 nm range) is expected to be > 1000

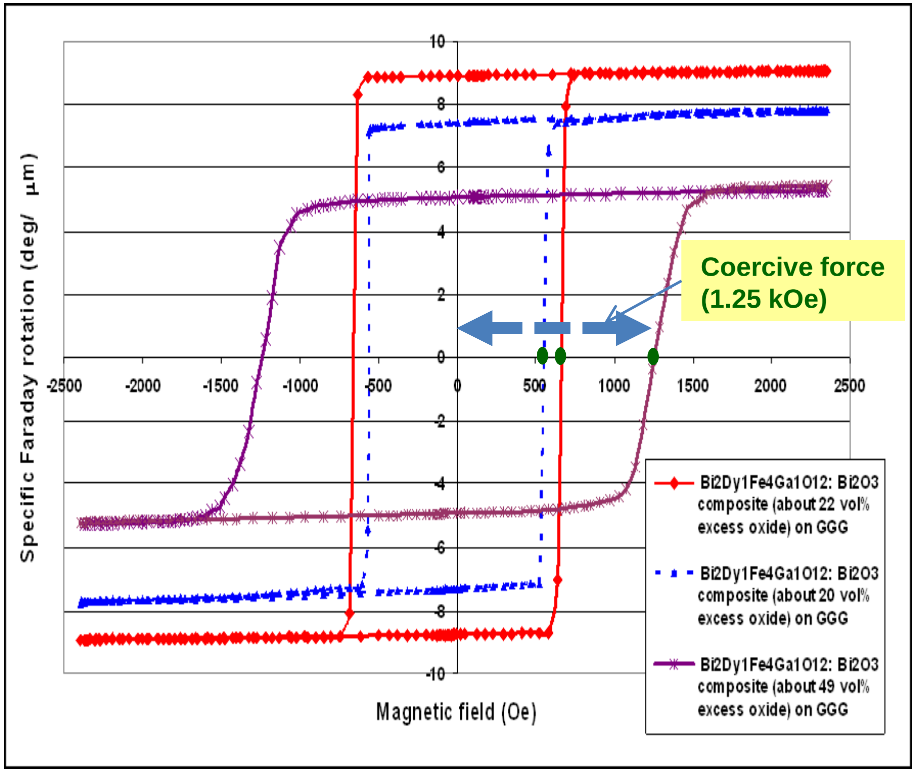
Crystal structure properties of $Bi_2Dy_1Fe_{5-x}Ga_xO_{12}$ thin film materials

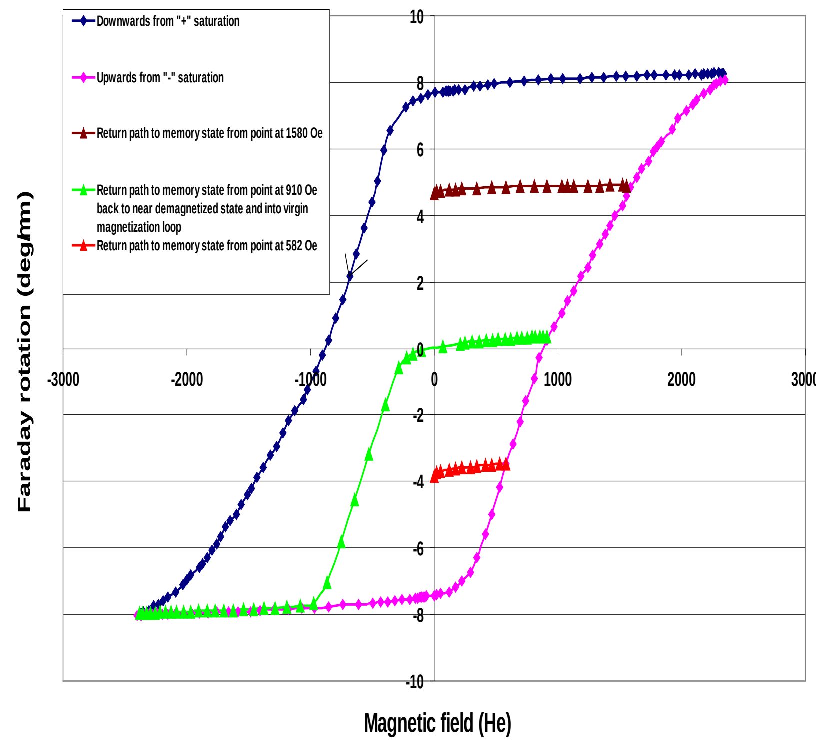


Stronger garnet-phase reflection peaks and weaker iron oxide peaks observed in high-performance oxide-mixed composites

- **Garnet phase with bcc cubic lattice type**
- **Crystal lattice parameters have been calculated from XRD data**
- **Average grain size 37 nm (agrees with TEM imaging results)**

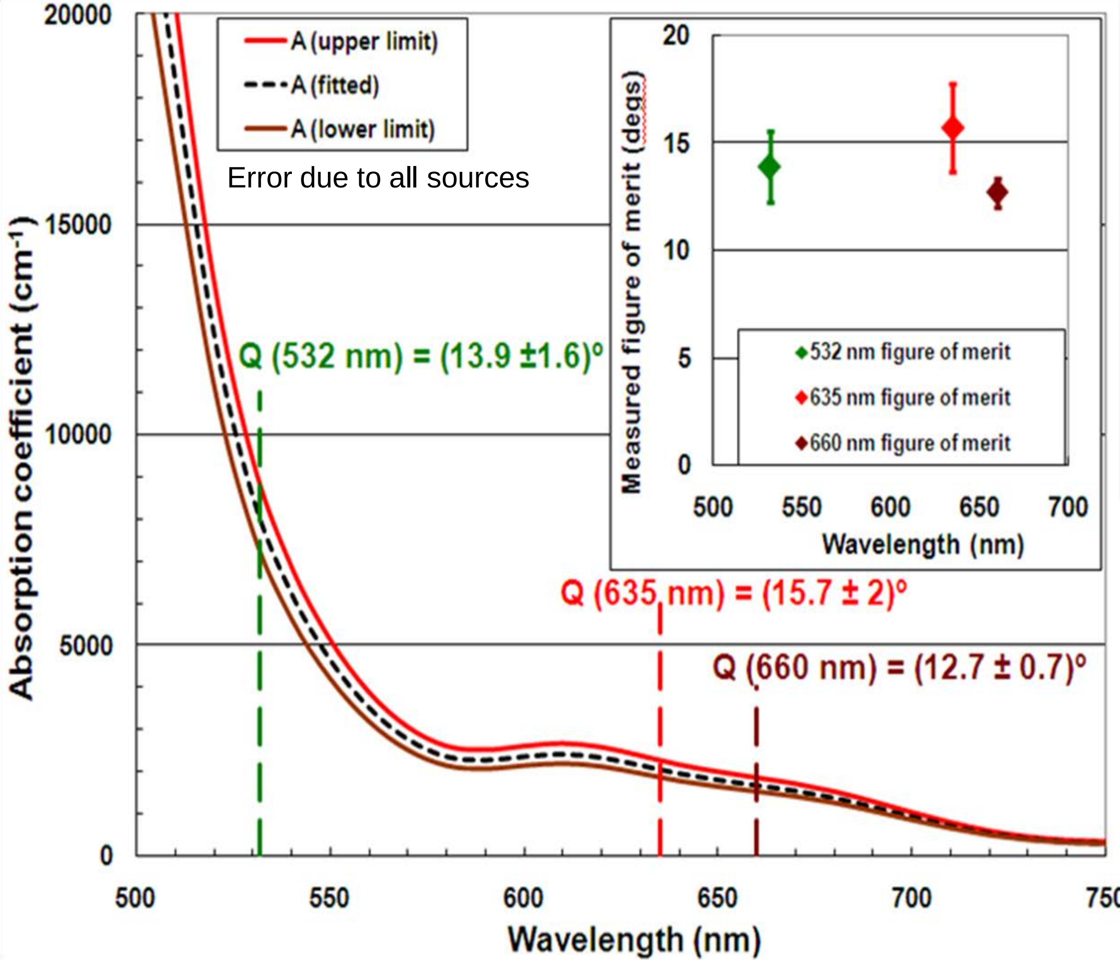
Magnetic properties of $Bi_2Dy_1Fe_{5-x}Ga_xO_{12}$ thin film materials





- **Control over the magnetic hysteresis loop properties of garnet layers – an area of our ongoing research; crucial for the design of integrated optic devices using Faraday effect**
- **Multiple remnant magnetization levels demonstrated in films with perpendicular magnetization** (M. Nur-E-Alam, M. Vasiliev, and K. Alameh, Opt. Quantum Electron. 41(9), 661–669, 2009).

$Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ Magneto-soft thin films



- **Low absorption coefficients observed**
- **High specific Faraday rotation**

❖ *5.9 deg/μm at 532 nm*

❖ *1.6 deg/μm at 635 nm*

❖ *1.07 deg/μm at 660 nm*

- **Measured MO quality factors ($2\Theta_F/A$)**

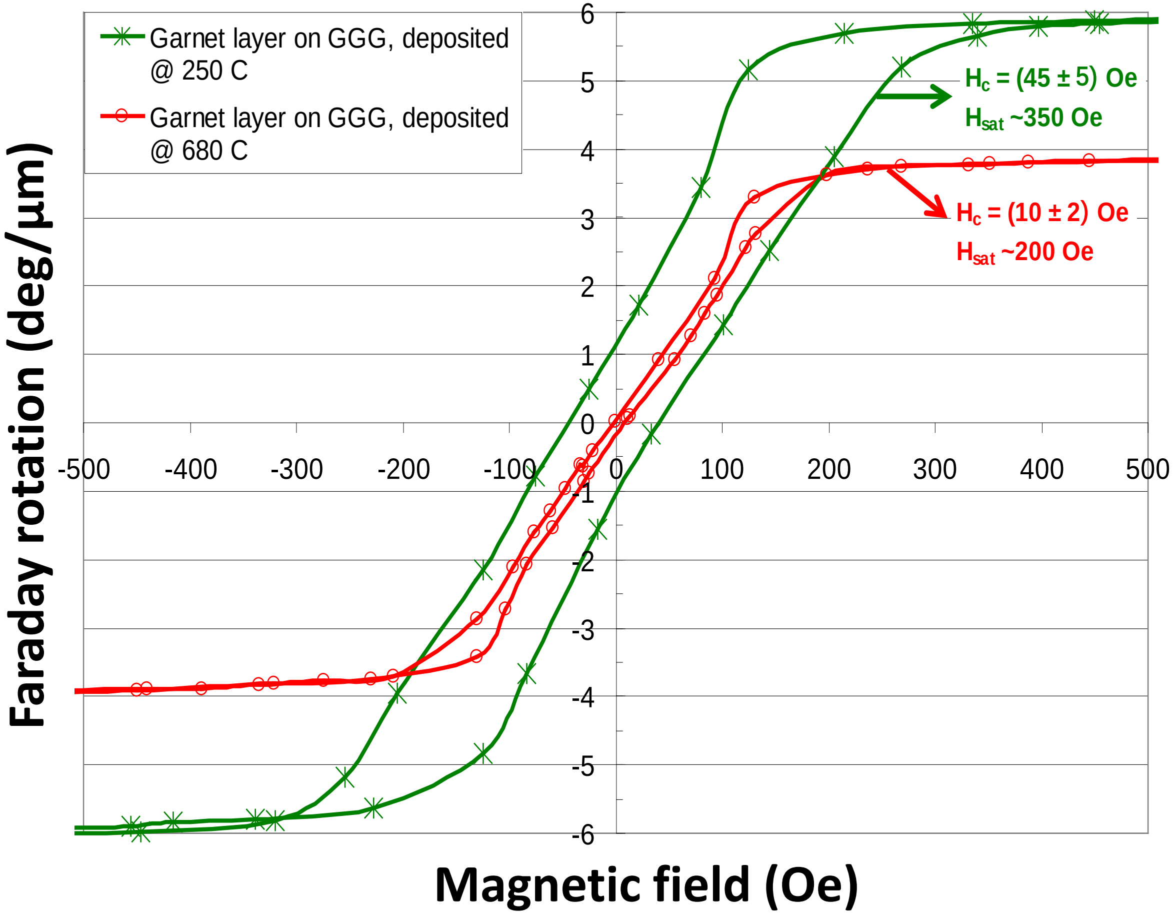
❖13.9° (±1.6°) at 532 nm

❖15.7° (±2°) at 635 nm

❖12.7° (±0.7°) at 660 nm

RF sputtered $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ magnetically-soft thin films are very attractive for different magneto-optic applications and for designing novel magnetically-controlled photonic components

Faraday-effect hysteresis loops



Hysteresis loop of $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ MO films deposited onto (GGG) substrates

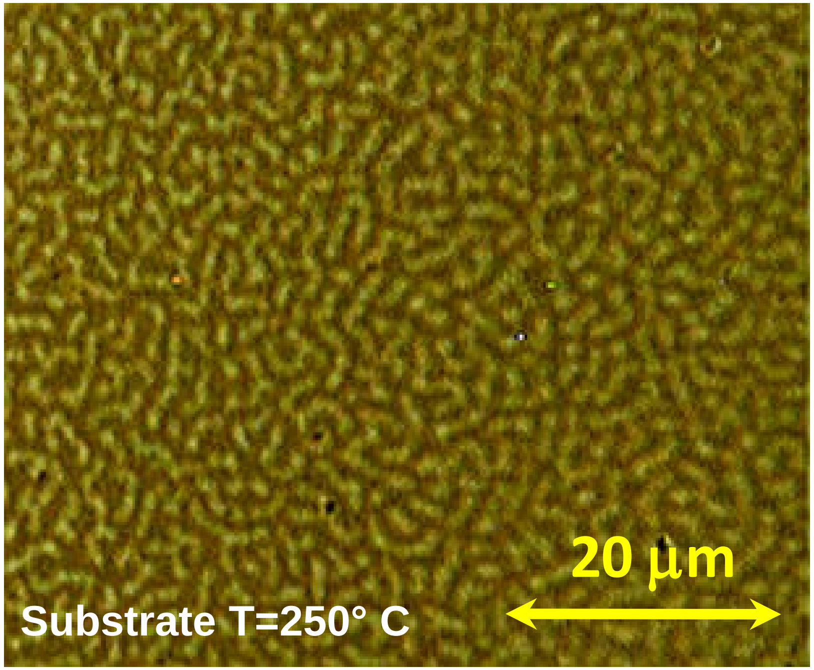
- Strong substrate dependency of coercive force observed
- H_c ~ 45 Oe for the films on GGG substrates deposited at 250 °C and **H_c below 10 Oe** obtained in films deposited at high substrate temperatures (680 °C).

•Measured Faraday-effect magnetic field sensitivity at 532 nm: **> 100 °/(cm·Oe)**

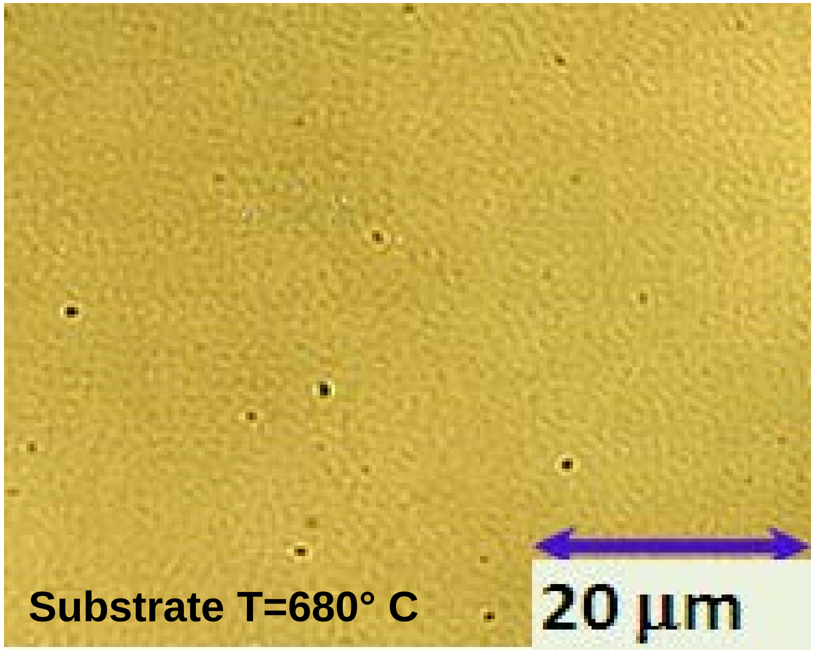
•Low coercive force ⇒ lower external magnetic field required to control light through polarisation

Magnetic domain structures: polarization microscopy

(a)



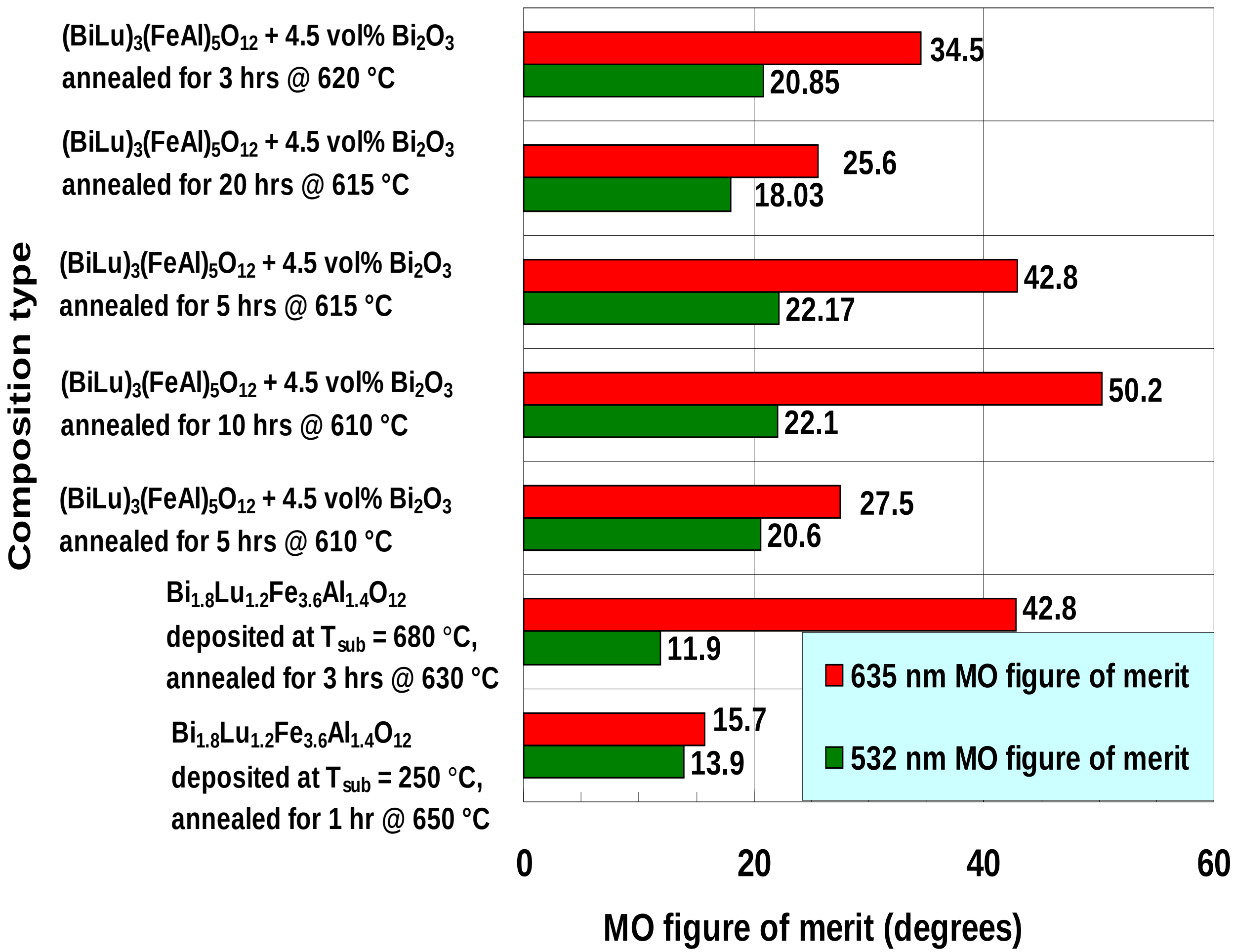
(b)



- ❑ Domain structures observed in the absence of external magnetic fields using transmission-mode polarization microscopy
- ❑ Regular maze-type domains were observed in sputtered $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ films deposited onto GGG at (a) 250 °C and (b) 680 °C substrate temperature
- ❑ Films deposited at high T(sub) are almost domain-free $\Rightarrow$ **almost in-plane magnetization**

Good crystalline quality, low coercive force values and high magnetic sensitivity achieved in our magnetically-soft garnet materials which are attractive for the development of reconfigurable nanophotonic devices and garnet waveguides

$Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$: Bi_2O_3 nanocomposites and engineering of the material properties

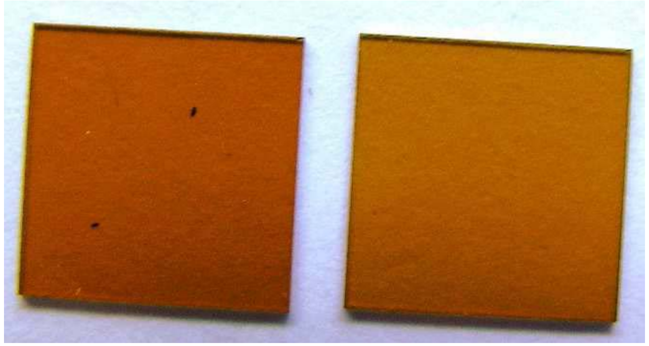


MO figures of merit measured in garnet and garnet-oxide composite films of type $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$: Bi_2O_3

The effects of adjusting the garnet stoichiometry by co-sputtering extra Bi_2O_3 have been studied; significantly improved material properties were achieved

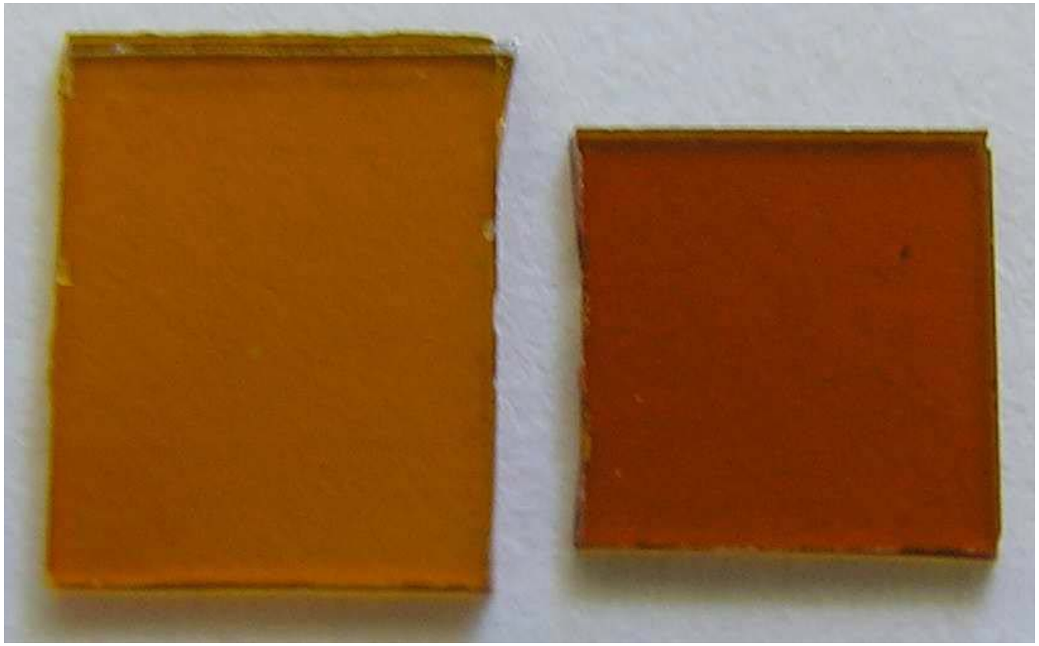
- High Faraday rotations observed
- Very low absorption coefficients measured (below 1000 cm^{-1} at 635 nm).
- High MO figures of merit measured at 635 nm (more than 50°)

Improved optical transparency achieved in nanocomposites



Left: 650 nm-thick film of $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ on a $Gd_3Ga_5O_{12}$ (GGG) substrate;

Right: 1150 nm-thick film of ($Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ + 20 vol.% co-sputtered Bi_2O_3) on a GGG substrate - both films are as-deposited

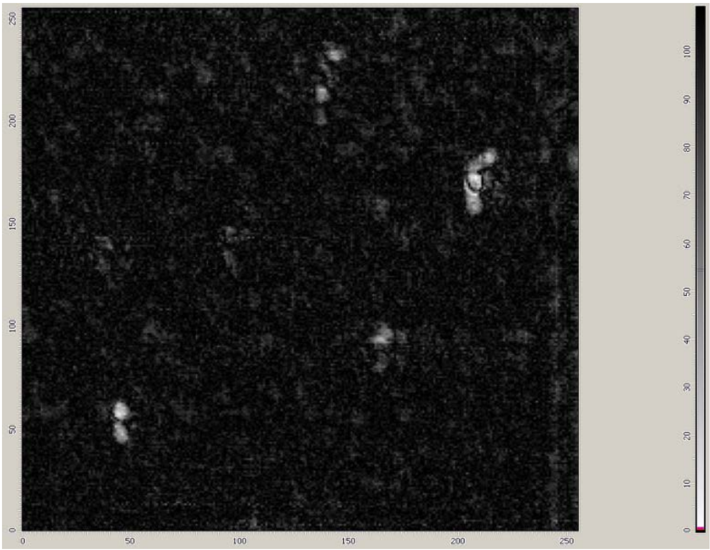


Annealed (crystallized) films:

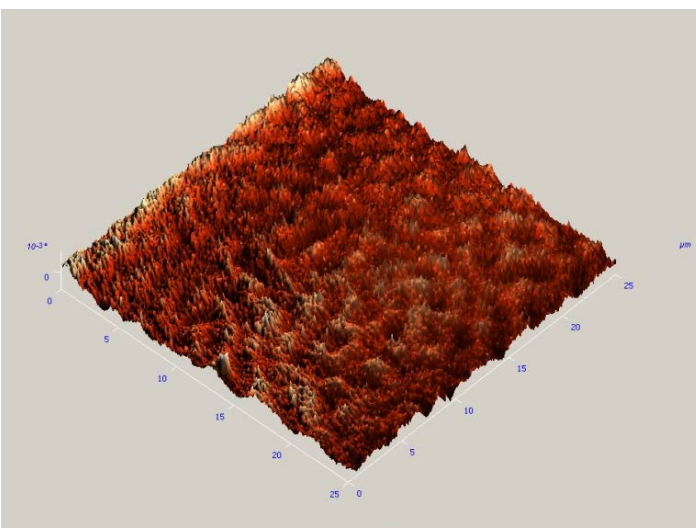
Left: 1030 nm-thick ($Bi_2Dy_1Fe_4Ga_1O_{12}$ +24 vol.% Bi_2O_3) on glass;

Right: 1080 nm-thick $Bi_2Dy_1Fe_{4.3}Ga_{0.7}O_{12}$ on GGG.

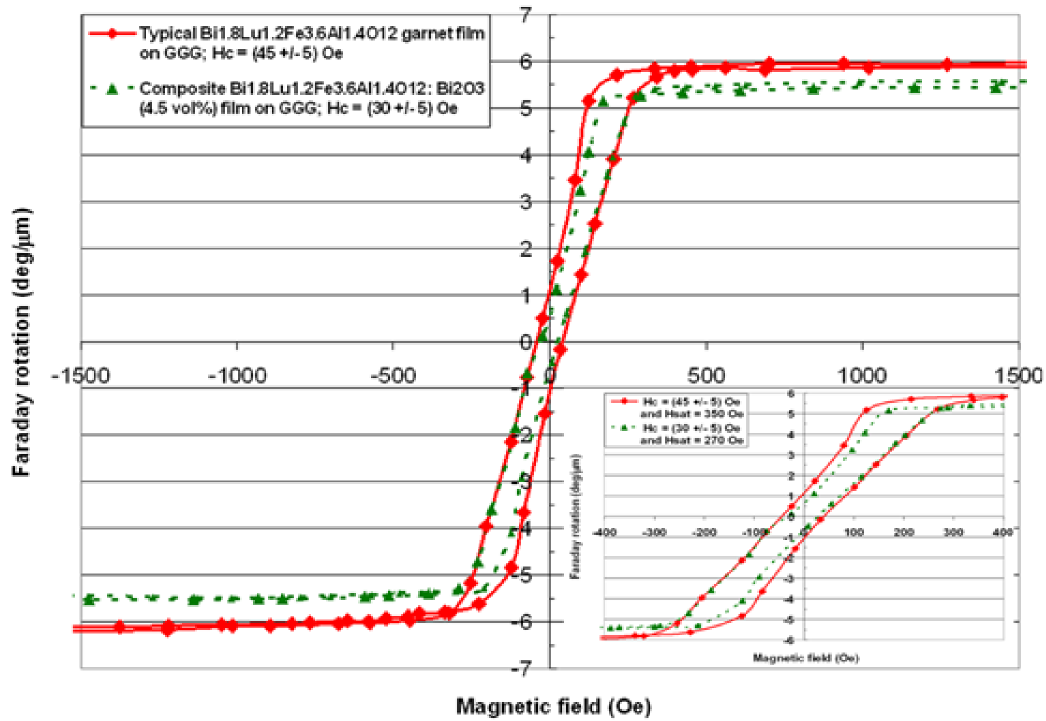
Surface morphology and magnetic properties of $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$: Bi_2O_3 nanocomposite thin films



2D image of garnet-oxide composite film



3D image of garnet-oxide composite film

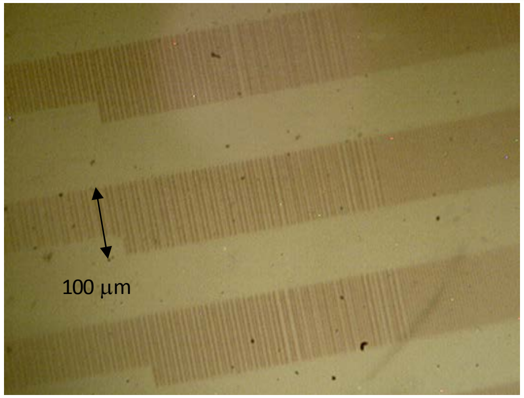


- ❑ Comparatively lower coercive force has been achieved for nanocomposite oxide-mixed films
- ❑ Nano-crystalline structure of garnet materials has been observed

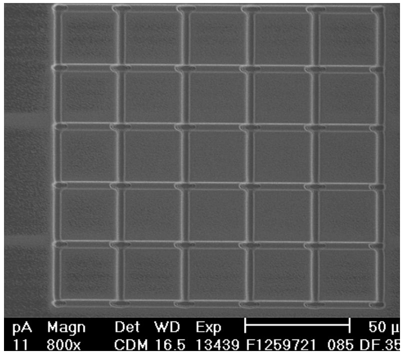
Applications of MO garnet films

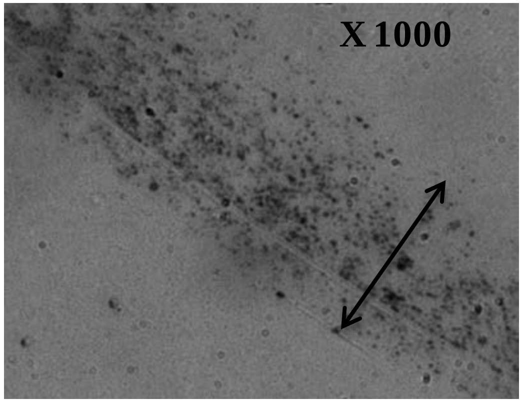
➢**The garnet and garnet-oxide thin film materials possess an excellent combination of optical, magnetic and MO properties.**

➢**Suitable for use in a wide range of emerging application areas**



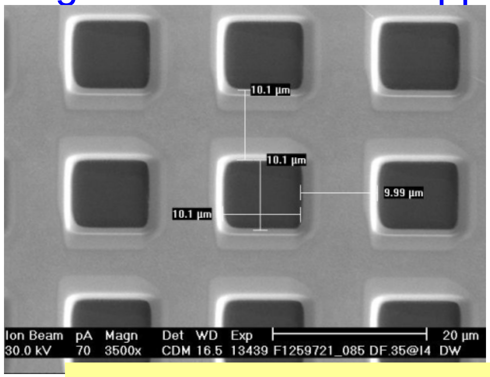
- *Nano-structured magnetic photonic crystals (MPC) for magneto-optic polarization controllers in a wide angular range (up to ± Θ_{Fmax})*
- *Ultrafast spatial or temporal modulators of light intensity*
- *Non-reciprocal waveguide components*
- *Dielectric permanent magnets with adjustable magnetic field landscapes over the film surface*
- *Nano-engineered high-contrast magnetic field sensors and visualisers*
- *Potential applications in biology (cell manipulation)*



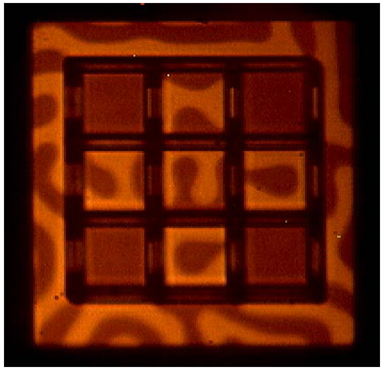


High resolution images of magnetic data tracks have been acquired using visible and UV polarisation microscopy

Magnetic lattices for trapping ultra-cold atoms



Asymmetrical 2D magnetic lattice formed using a film of $Bi_2Dy_1Fe_4Ga_1O_{12}$ sputtered onto a Si substrate (A. Abdelrahman et al, Phys. Rev. A 82(1), 012320, 2010).

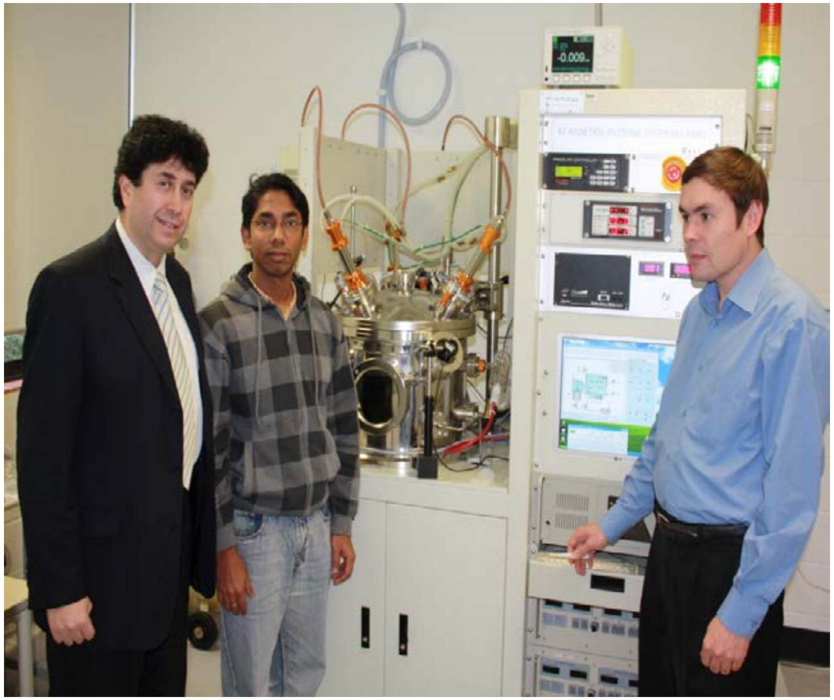


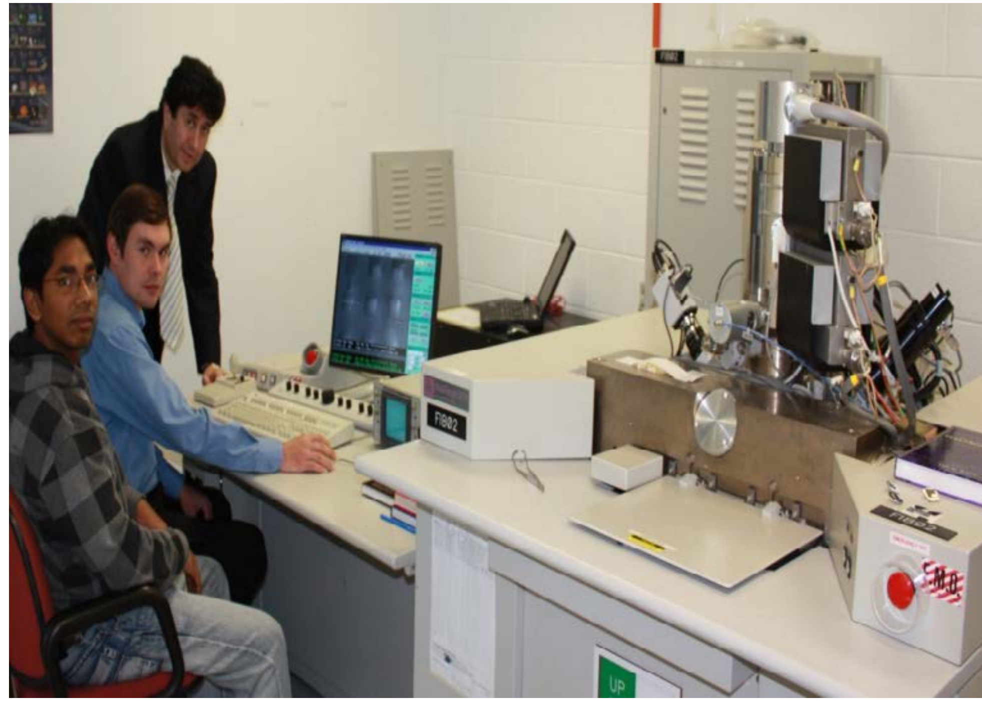
Ultra-fast spatial light modulators and image recognition systems

CONCLUSION

- Bi-substituted MO garnet thin-film materials (both magnetically-soft and hard) with excellent optical and record-high MO quality have been demonstrated
- Sputter-deposition and oven annealing processes required for the manufacture of high-quality garnet films have been studied and the process parameters were optimized
- The combination of material properties achieved is of interest for the development of different emerging types of reconfigurable nano-photonic devices
- Our research work will be continued to further optimize the material properties and demonstrate the potential of garnets in a range of new applications

Thank you





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