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New Class of Garnet Nanocomposites for Use in Magnetic Photonic Crystals Prepared by RF Magnetron Co-sputtering

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OUTLINE

- Introduction (magnetic garnets and their applications)
- Material synthesis and characterization
    - RF magnetron sputtering deposition
    - Co-sputtering of $Bi_3Fe_5O_{12}$ - $(Bi, Dy)_3(Fe, Ga)_5O_{12}$ material system using two separate deposition sources
    - Crystallization of garnet layers (annealing process)
- Properties of RF sputtered $(Bi, Dy)_3(Fe, Ga)_5O_{12}$ garnet thin films
- Properties of $Bi_3Fe_5O_{12}$ - $(Bi, Dy)_3(Fe, Ga)_5O_{12}$ nano-composites
- Conclusion

Introduction to Rare Earth Iron Garnets

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

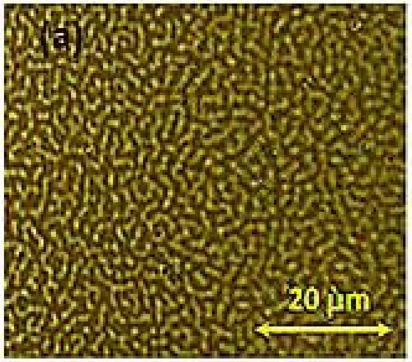
❖ **Highest specific Faraday rotation in the visible and near-IR regions**

Commonly known garnet materials are:

Yttrium Aluminium Garnet (YAG = $Y_3Al_5O_{12}$),
Yttrium Iron Garnet (YIG = $Y_3Fe_5O_{12}$),
Gadolinium Gallium Garnet (GGG= $Gd_3Ga_5O_{12}$) and
Bismuth-substituted Iron Garnet (BIG = $Bi_3Fe_5O_{12}$)

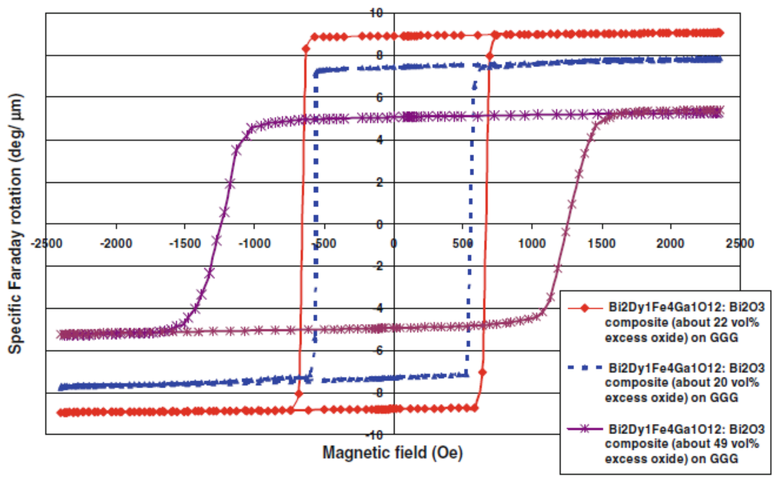
Bismuth-substituted iron garnets doped with Gallium $(Bi, Dy)_3(Fe, Ga)_5O_{12}$, are an important subclass of garnets, useful for magnetic and MO applications

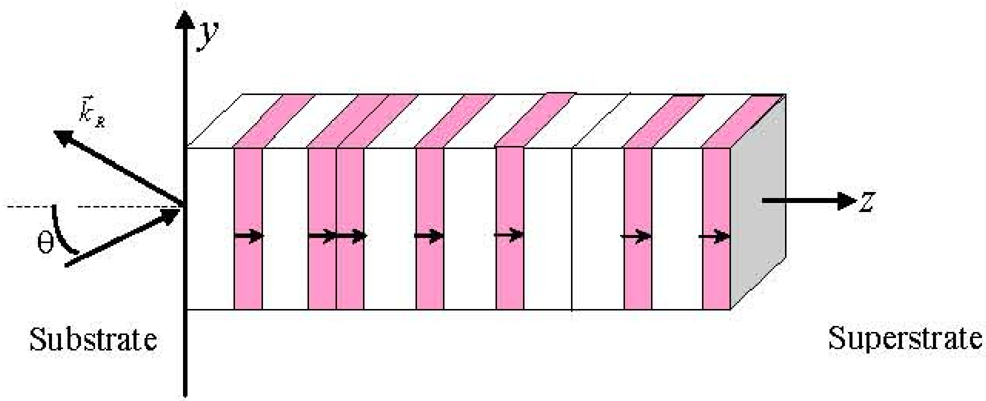
- non-reciprocal optical components (Faraday rotators)
- magnetic recording media (bubble memory)
- magnetic field sensors
- MO imaging and visualisation
- MO planar waveguides
- magnetically-tunable photonic crystal devices (MPC)



Applications of garnet films and MPC

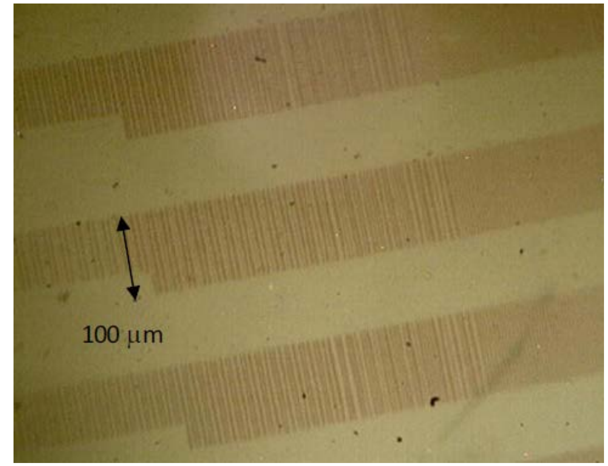
Ultrafast magnetic switching and modulation of light intensity





1-D Magnetic Photonic Crystal (a schematic diagram; arrows indicate the magnetization direction)

Magneto-optic (MO) imaging/sensing

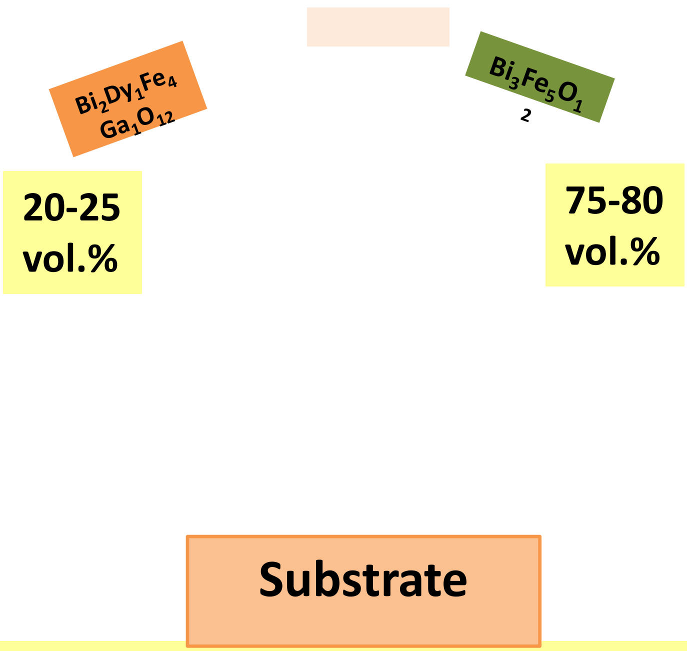


MPC are nanostructured artificial functional media containing magnetic constituents

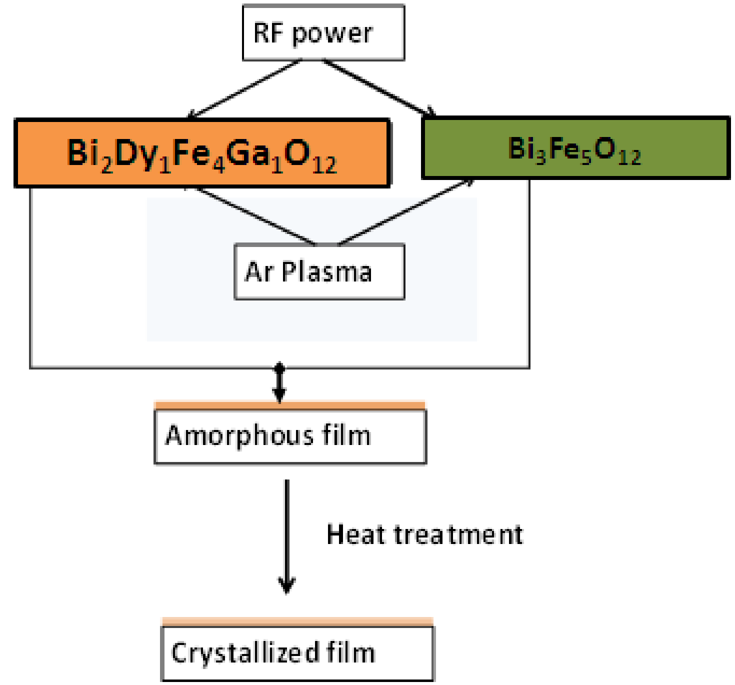
Many MO effects (Faraday, Kerr, Voigt etc) can be enhanced by designing MPC structures

Like metamaterials, MPCs can demonstrate new effects, but the magnetics are usually dielectric, not metals

MO thin films manufacture (PVD+annealing)



Schematic diagram of the co-sputtering system geometry



Flow chart of garnet nano-composite co-sputtered thin films processing

❖ Optimization of process parameters is crucial for the development of new materials and engineer the material properties for emerging applications and technologies in optics and photonics

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

Synthesis of thin-film garnet materials

Magnetron sputtering systems available at Electron Science Research Institute, ECU, Australia

RF Magnetron sputtering (down sputtering) system

RF Magnetron sputtering (up sputtering) system

Garnet nanocomposites prepared by composition adjustment in the $Bi_3Fe_5O_{12}$–$Bi_2Dy_1Fe_4Ga_1O_{12}$ material system

Why co-sputter $Bi_3Fe_5O_{12}$– $Bi_2Dy_1Fe_4Ga_1O_{12}$ materials

➢ **Increase the number of bismuth atoms per unit formula in the sputtered films**

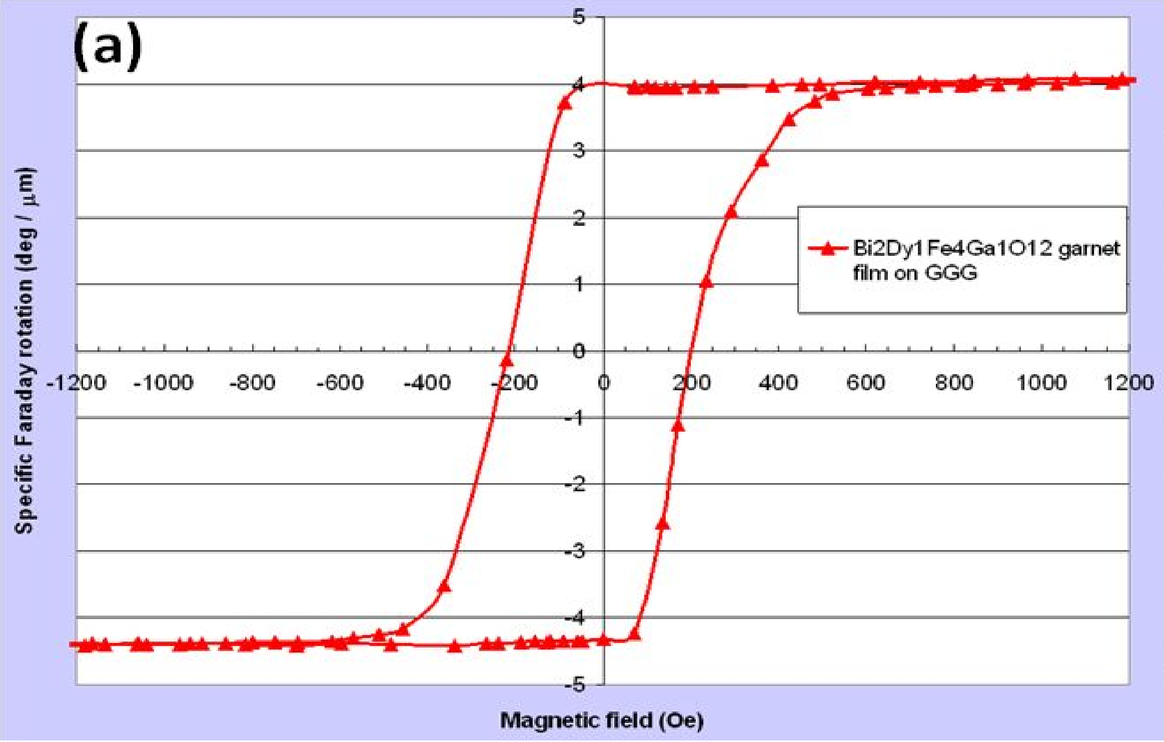
➢ **Hard to crystallize any RF-sputtered garnet-type materials from targets containing five iron atoms per stoichiometric formula unit (without any Ga or Al dilution)**

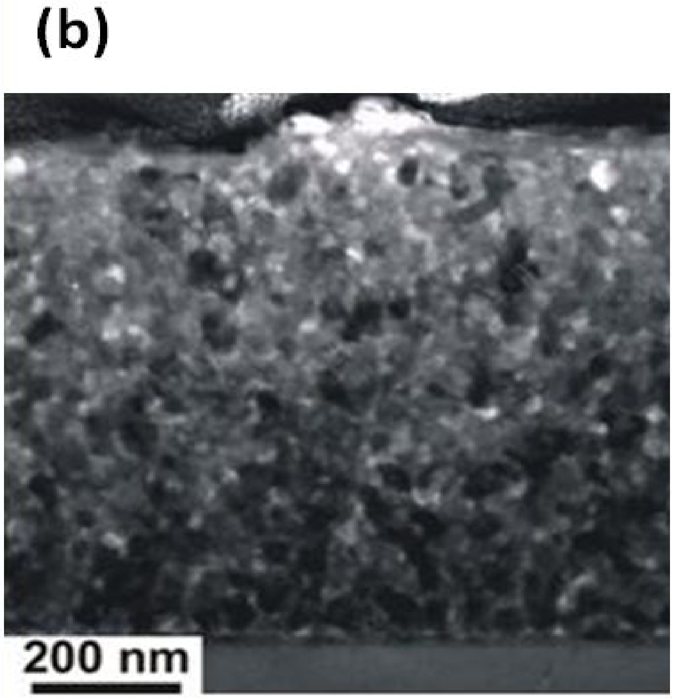
➢ **One of the best approaches of synthesizing a garnet composition as close as possible to $Bi_3Fe_5O_{12}$ which still contained some Ga and Dy substitution**

➢ **Investigate the effects of increasing the Bi substitution towards 3 f.u. in terms of changes in the magnetic properties**

- **This new garnet nanocomposite exhibits a significant "red-shift" of the main MO transitions that define the MO properties**
- **The material has high Faraday rotation, good MO quality and magnetization direction perpendicular to the film plane**
- **Useful for magnetic photonic crystals (MPC) and Faraday rotators**

Properties of $Bi_2Dy_1Fe_4Ga_1O_{12}$ thin films





- The parameters of importance are: absorption coefficient and specific Faraday rotation spectra
- Optimization of MO properties is vital for the design of all magneto-photonic structures

Optical properties of garnet layers depend significantly on the material phase

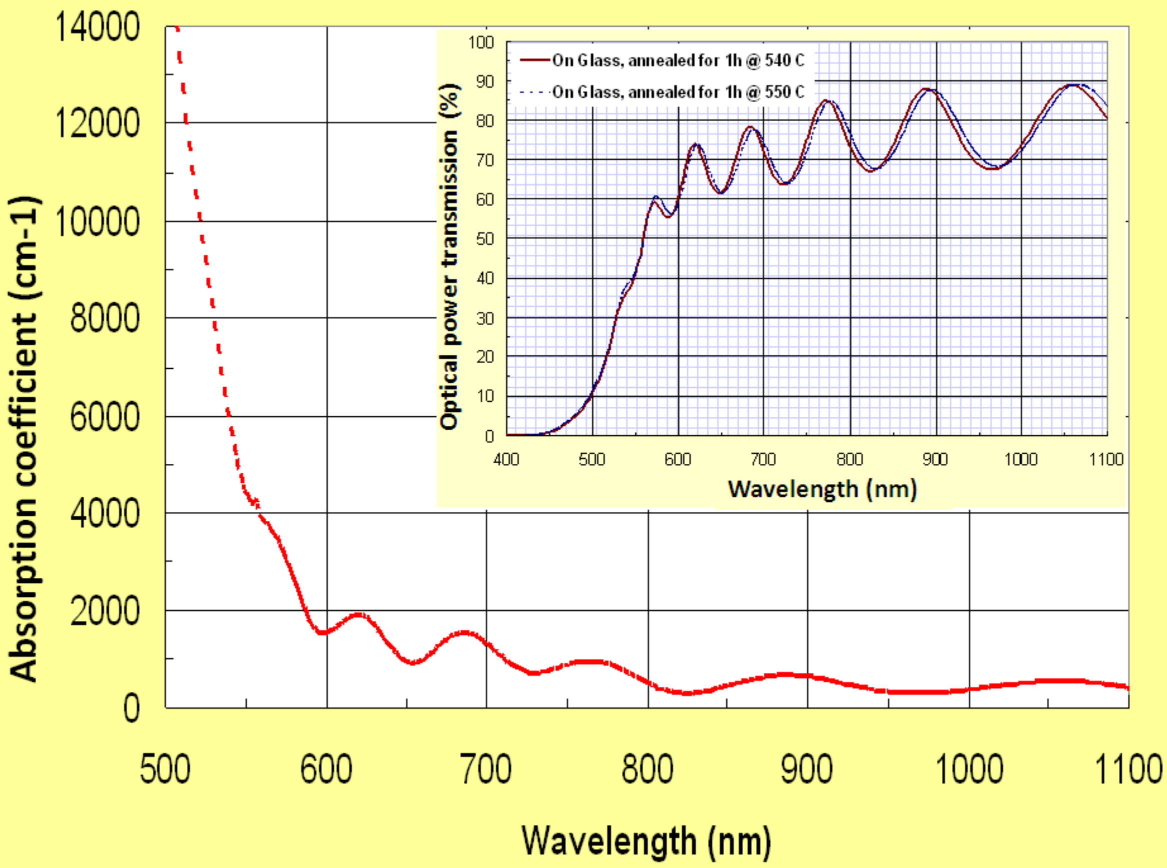
Material's phase formation depends on the process parameters

Materials' Figure of Merit = Q = 2 * $|\Theta_F|$ / A; Θ_F = 0.1 – 10 °/µm; A = 0.01 – (> 7000 cm^{-1})

We achieved: Q (green) ≈ 30; Q (red) ≈ 45 in Garnet-Bismuth Oxide composite films;

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

Properties of $Bi_3Fe_5O_{12}$– $Bi_2Dy_1Fe_4Ga_1O_{12}$ nano-composite thin films



Absorption spectrum of a garnet nanocomposite film prepared on glass substrate

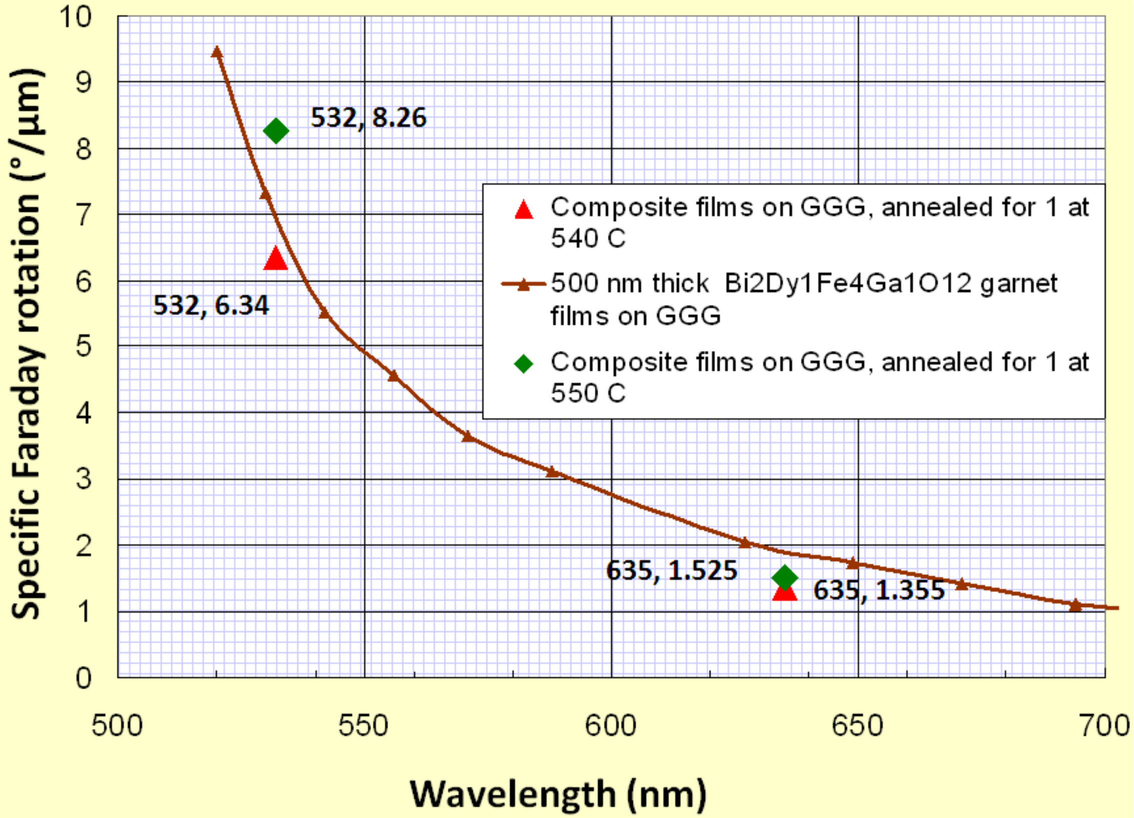
Properties of importance:

- Optical transmission and absorption spectra of both the as-deposited and post-annealed garnet layers
- Faraday rotation per unit thickness and especially *its spectrum* $F(\lambda)$

All of these properties are governed by the material composition and microstructure

The absorption spectra were derived using iterative fitting of the spectral features observed in the measured and modeled transmission spectra of the films (Optics Express Vol. 17(22), 19519-19535, 2009)

Properties of $Bi_3Fe_5O_{12}$– $Bi_2Dy_1Fe_4Ga_1O_{12}$ nano-composite thin films



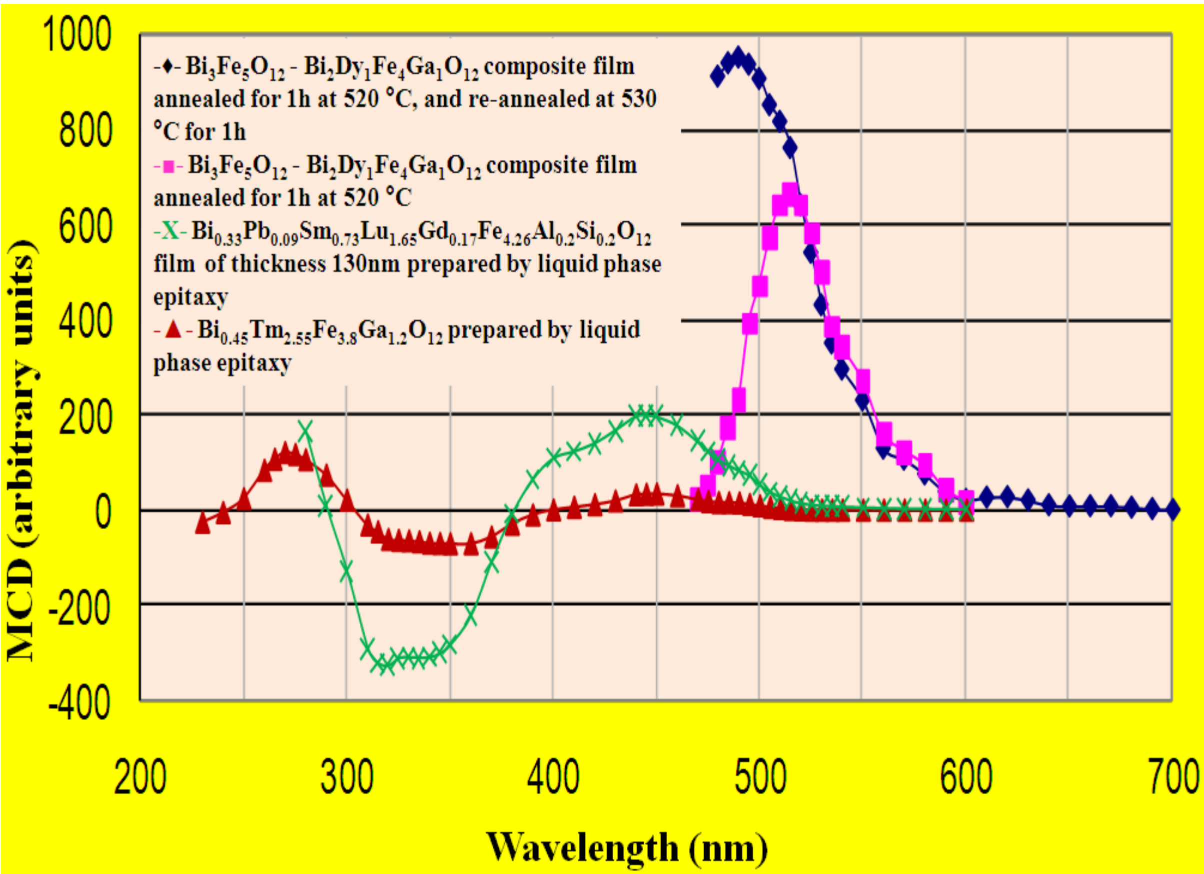
Measured specific Faraday rotation data points of garnet nanocomposite films at 532 and 635 nm

- ❖ High Faraday rotation of > 8.2 °/μm at 532 nm
- ❖ Good surface quality
- ❖ Almost 100% remnant magnetization
- ❖ High uniaxial magnetic anisotropy (the magnetization direction of films is perpendicular to the film's plane)
- ❖ Successful crystallization of a garnet system with Bi content of > 2.2 f.u.

In MO garnets with Bi content approaching 3 f.u., nonlinear Faraday-effect growth vs Bi content was reported (Ref. 2 in our paper)

Properties of $Bi_3Fe_5O_{12}$– $Bi_2Dy_1Fe_4Ga_1O_{12}$ nano-composite thin films

A significant spectral "red-shift" effect affecting the main MO transitions in all of the co-sputtered samples was observed in their MCD spectra



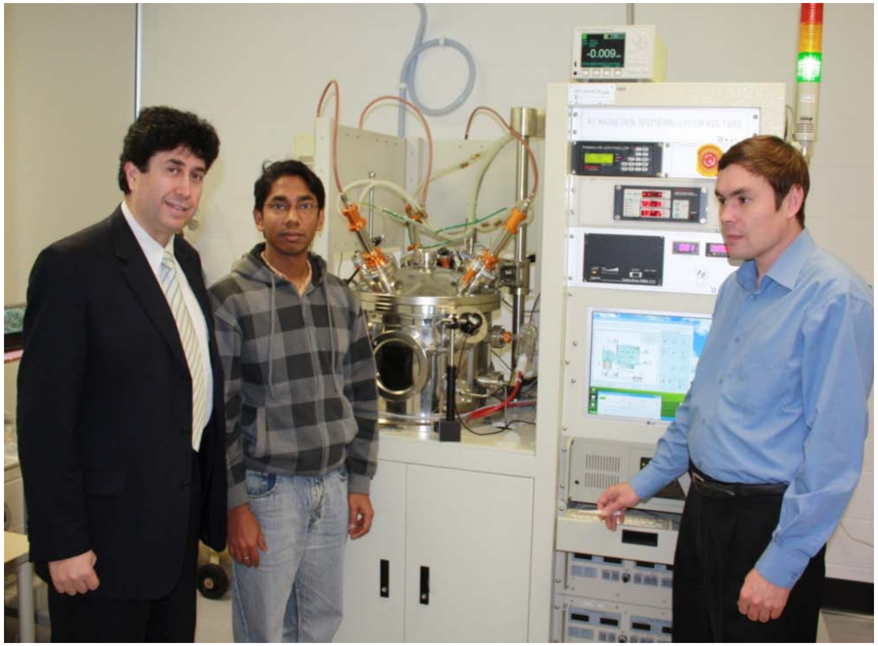
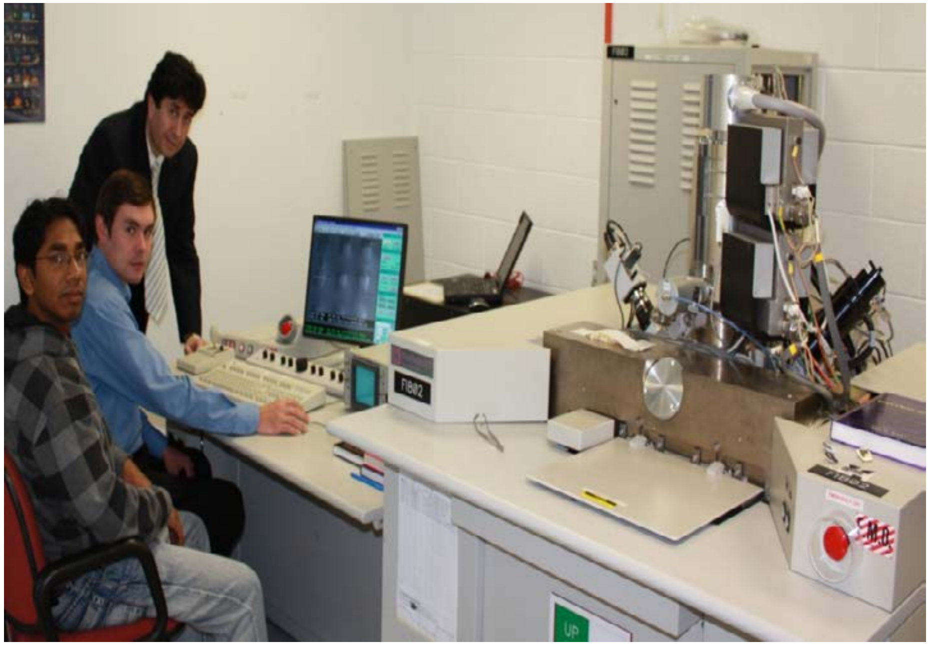
- ❖ Annealing temperature dependent MCD peak location observed
- ❖ Two broader MCD peaks at 495 nm with a small shoulder at 515 nm were observed in the films annealed at higher temperature
- ❖ A slight difference in the annealing temperature led to a significant difference in the material phase content

Magnetic circular dichroism (MCD) signals measured (in arbitrary units)

CONCLUSIONS

- A new class of garnet nano-composites with high Faraday rotation and good MO quality has been synthesized and studied
- Sputter-deposition and oven annealing processes required for the manufacture of high-bismuth-content garnet films have been studied and the process parameters were optimized
- A significant spectral "red-shift" effect affecting the main MO transitions in all of the co-sputtered samples was observed in the MCD spectra
- The combination of material properties achieved is of interest for the development of different emerging types of magnetically-reconfigurable nano-photonic devices
- Our work will be continued to further optimize the process conditions and better control the lattice parameters of garnet materials and also to synthesize new classes of MO garnets.

Thank you

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