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Nanostructured engineered materials with high magneto-optic performance for integrated photonics applications

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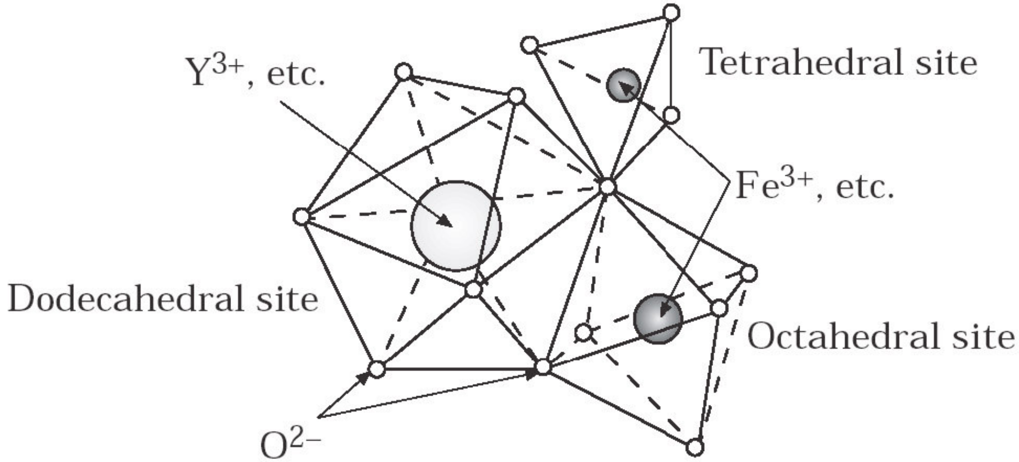
OUTLINE

- Introduction
  - Garnet materials and their properties
  - Magnetic Photonic Crystals (MPC)
  - Magneto-optic imaging and other applications
- Manufacturing technology
  - RF Magnetron sputtering & annealing
  - Characterisation of garnet layers – results achieved
- Preliminary fabrication of simple and complex MPCs & issues to be solved
  - Observed microstructure and optical properties
  - MO imaging examples and magnetic domain patterns
  - Advantages of doped iron garnets with perpendicular magnetic anisotropy for MPC/MO imaging and tunable photonic crystals
- Conclusions and future work

Introduction: garnet materials & properties

Generic formula of rare-earth iron garnets: $R_3Fe_5O_{12}$ where R is a rare earth



Crystal structure of magnetic garnets

- **Tetrahedral & octahedral sublattices coupled anti-ferromagnetically ⇒ crystals with ferrimagnetic properties**

- **Extraordinary magnetooptical properties first reported by Buhrer (J. Appl. Phys. 40, 1969).**
- **Bi:YIG still being considered as best MO material for photonic crystal structures (highest Faraday rotation in visible and near IR)**

- 20 atoms per formula unit; 160 ions per unit cell of cubic lattice

- Commonly known garnets are:

YIG = $Y_3Fe_5O_{12}$,
GGG = $Gd_3Ga_5O_{12}$,
BIG = $Bi_3Fe_5O_{12}$

- A less commonly known but important subclass of garnets is described by the formula:

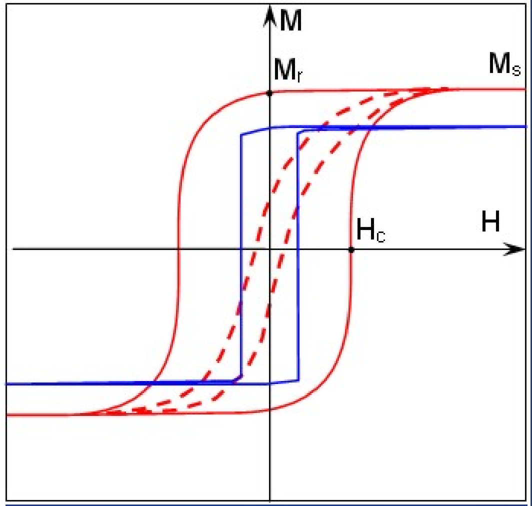
$(Bi, Dy)_3(Fe, Ga)_5O_{12}$

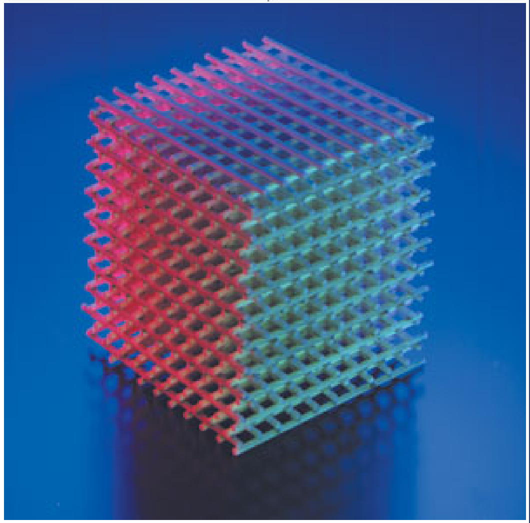
- Gallium-doped bismuth dysprosium iron garnet, useful for magnetic recording

Magnetic Photonic Crystals (MPC)

Photonic Crystals + Magnetisation

- **Periodic modulation** of optical properties on a sub-wavelength scale
- **Enhanced MO effects:**
  - Faraday effect
  - Voight effect
  - Kerr effect
- **Tunability** of the optical properties using external magnetic fields



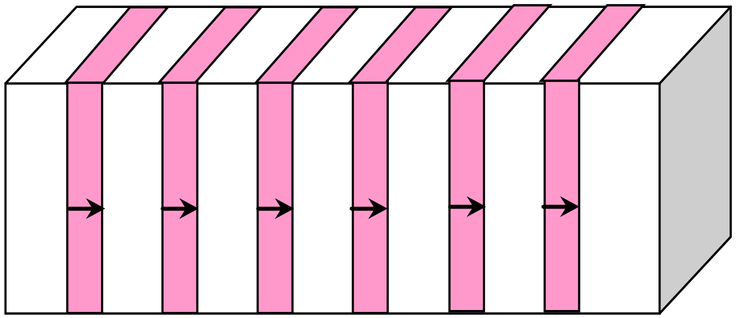


MPCs are unique because they combine:
1. Structural periodicity
2. Crystalline-phase layers

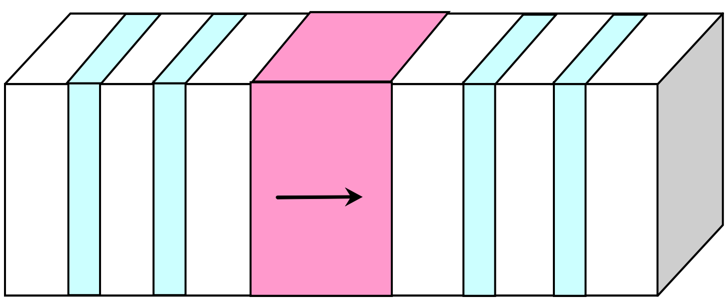
1D Magneto-Photonic Crystals (MPC)

Magnetic/Nonmagnetic λ/4n - layers

Perfect periodicity

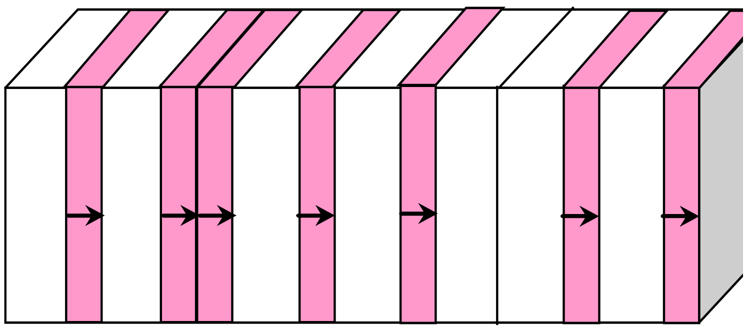


$$(MN)^a$$



$$(N_1N_2)^a(M)^b(N_2N_1)^a$$

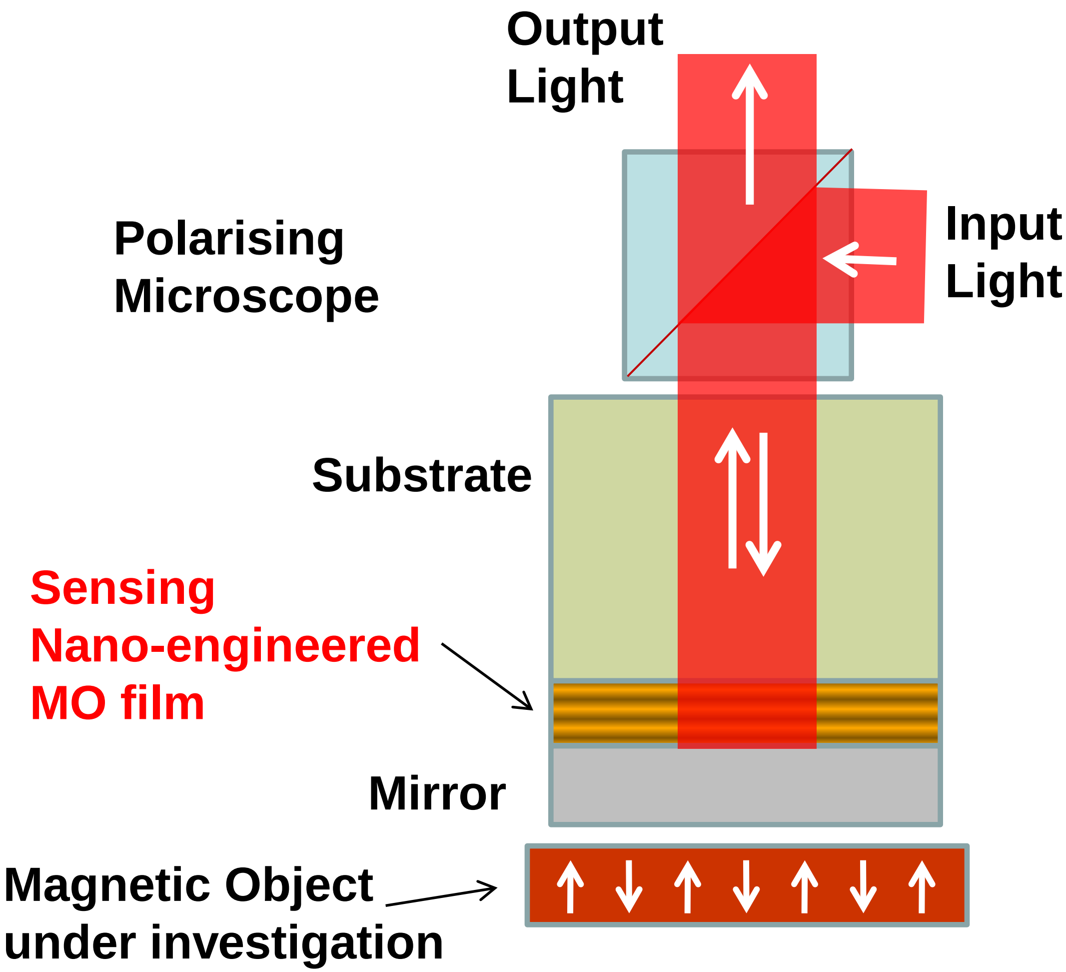
Quasi-periodicity with defects (phase shifts)



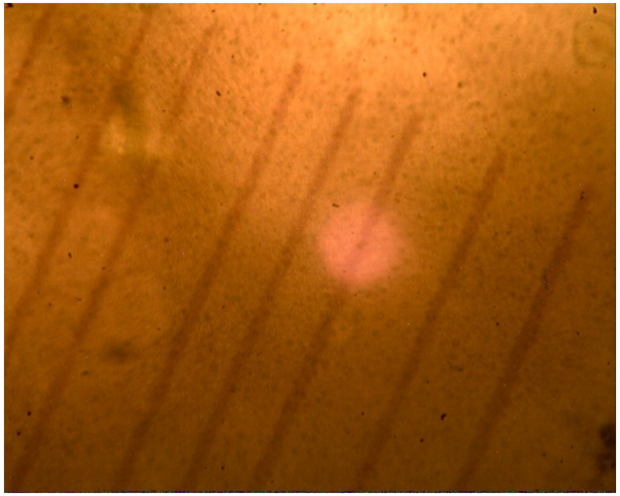
$$(MN)^a(NM)^b(MN)^c......(NM)^z$$

M = Bi-substituted doped iron garnet in its ferrimagnetic phase: YIG, Bi- or Ce-substituted, (Bi, Dopant1)$_3$(Fe,Dopant2)$_5$O$_{12}$
N = GGG ($Gd_3Ga_5O_{12}$), SiO_2, other dielectrics

Nano-engineered field visualisers & sensors



Operation of MO sensor/visualizer in reflection mode.



COMPS WA CENTRE OF EXCELLENCE FOR MICROPHOTONIC SYSTEMS

Manufacturing technology

AUSTRALIA ECU EDITH COWAN UNIVERSITY

Main technologies for MPC manufacture:

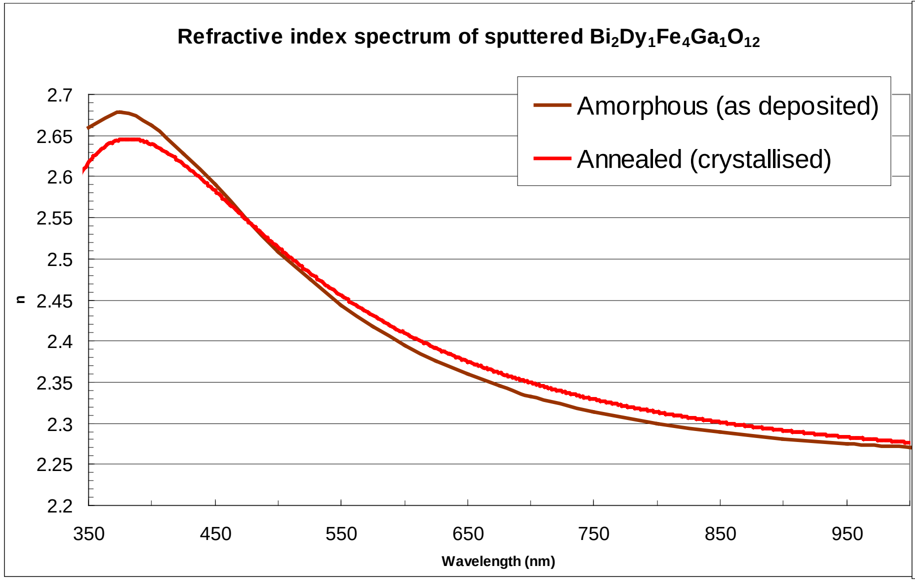
- Liquid-phase epitaxy (LPE)
- RF Magnetron sputtering (most common)
- Pulsed laser deposition (PLD)

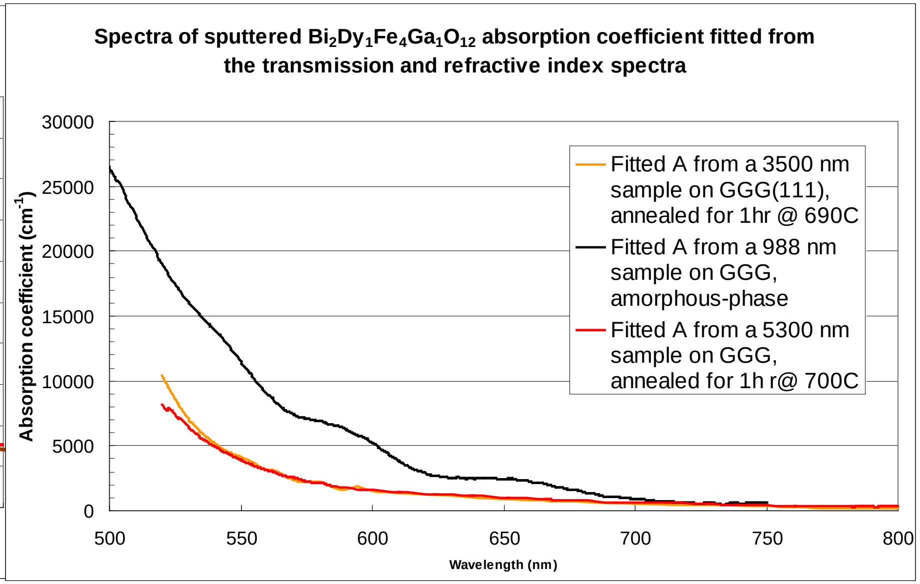
Current MPC manufacturers

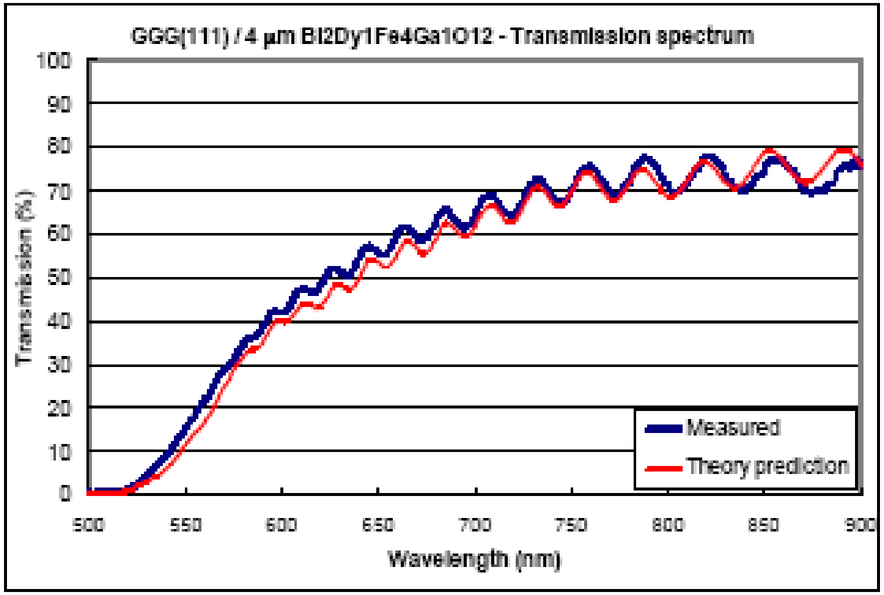
- Royal Institute of Technology, Stockholm, Sweden
- Toyohashi University of Technology, Japan
- ECU, Australia

RF Magnetron sputtering system

Characterisation of garnet layers





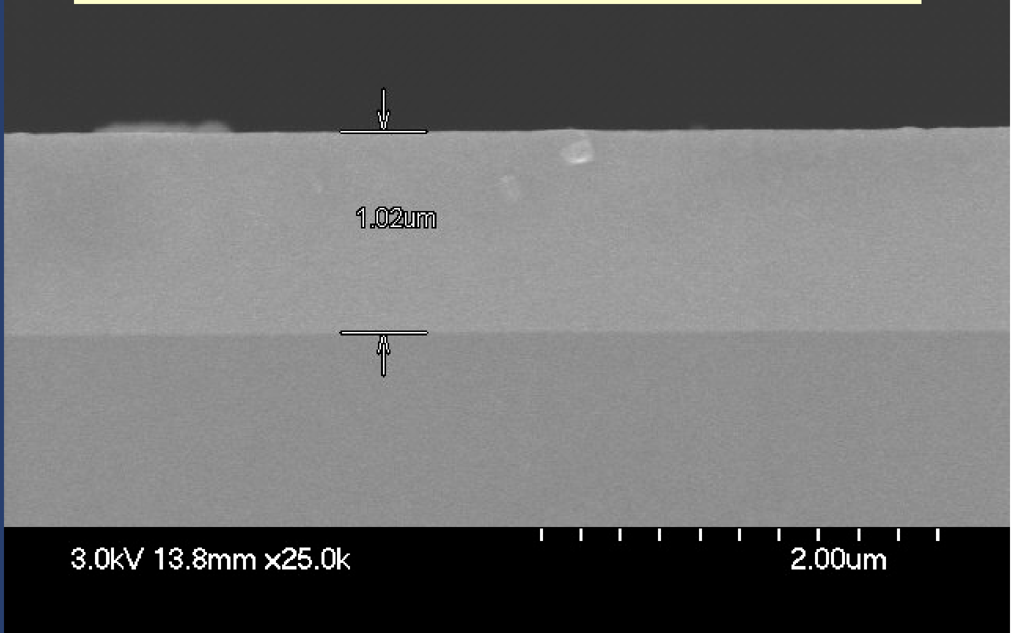


Optical properties of garnet layers depend significantly on the material phase.

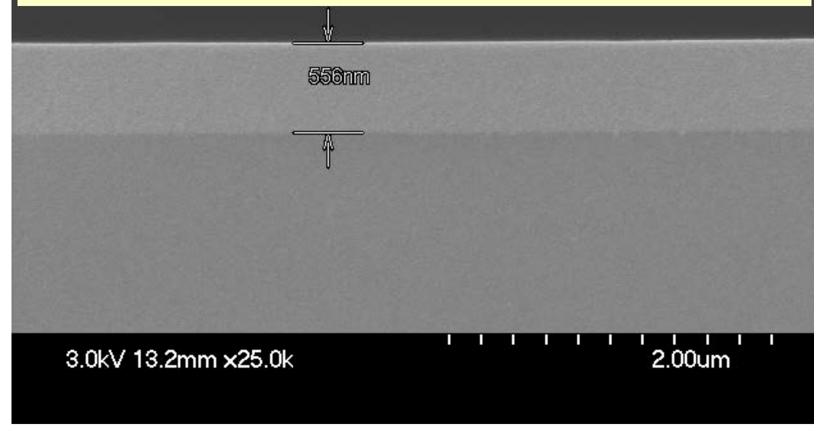
Optimum annealing regimes depend critically on material composition and layer deposition process used, and must be found experimentally for each garnet composition.

Layer microstructure

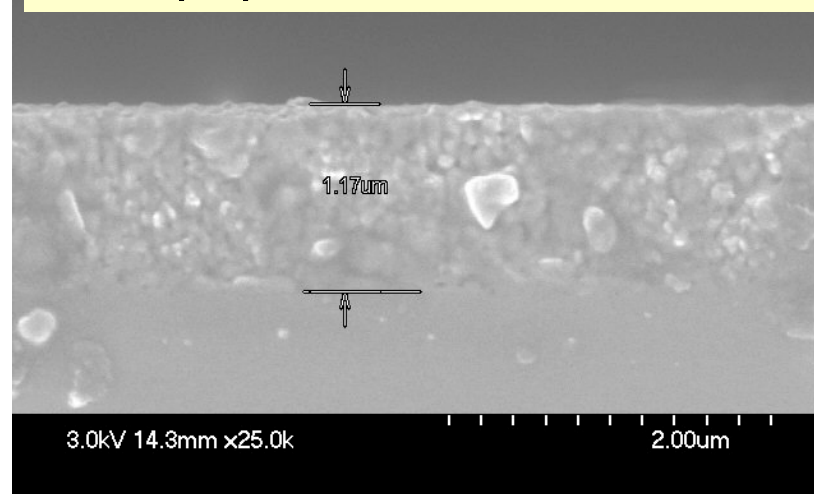
Amorphous 1020 nm of Bi2Dy1Fe4Ga1O12 on Corning7059 glass substrate.



A high-quality annealed garnet layer on a glass substrate



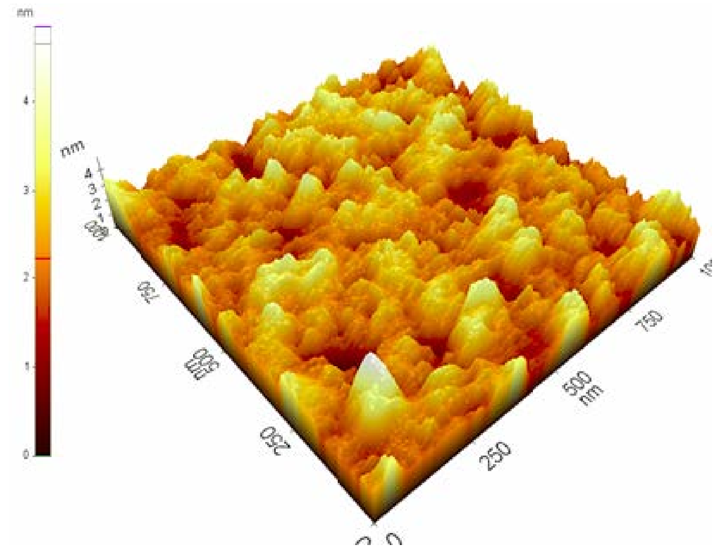
A possibly over-annealed garnet layer on a GGG(111) substrate



Annealing at 600 – 700 ºC (T is <u>very</u> composition-dependent) is necessary to crystallise MO material layers

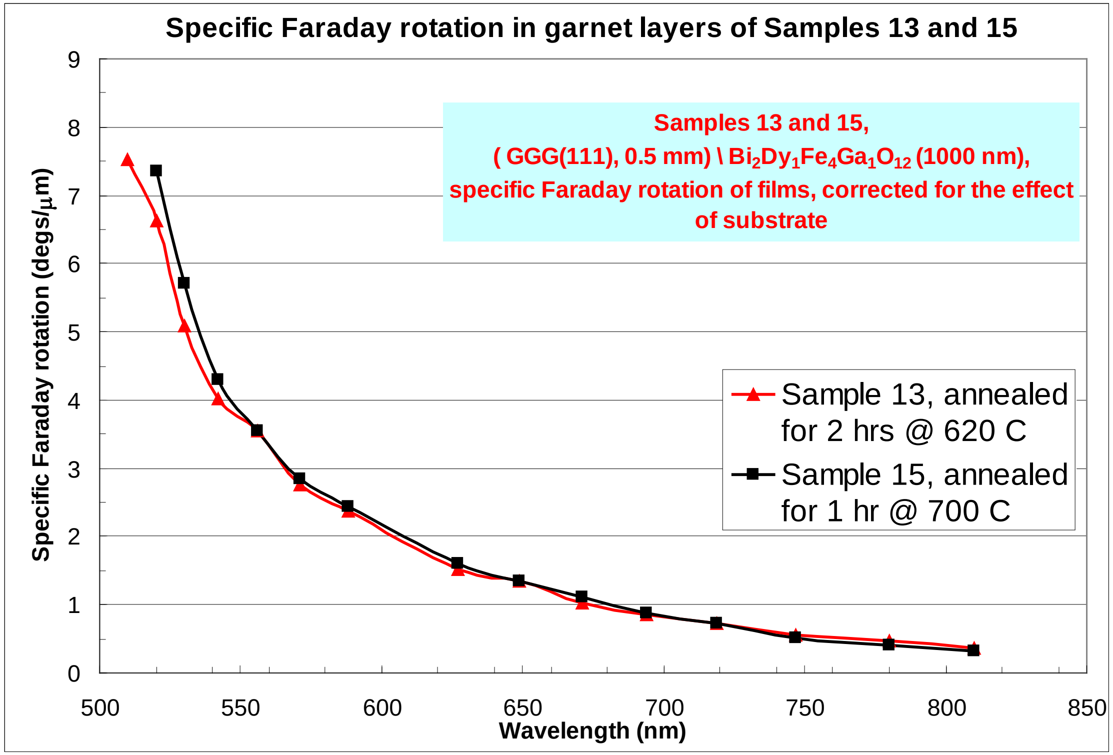
The goal is to achieve polycrystalline garnet phase with small-size grains (< 50 nm) and smooth layer surfaces

Manufacture and characterisation of high-quality garnet layers



Surface quality inspection (AFM)

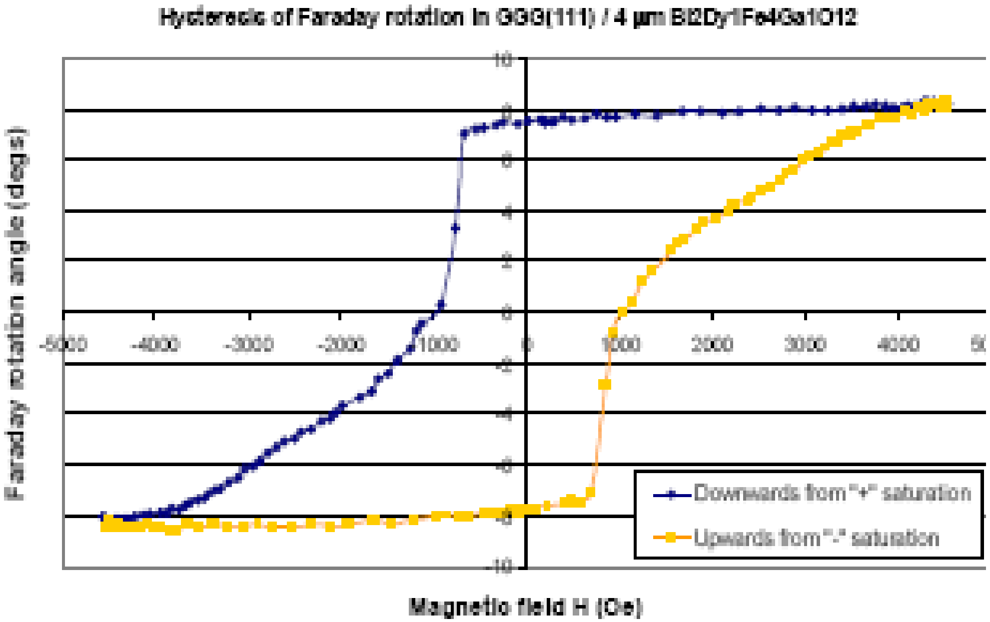
Mean RMS roughness in annealed layers (sampled across three 10x10 μm^2 locations) is about 5 nm.
For amorphous layers, about 1 nm.

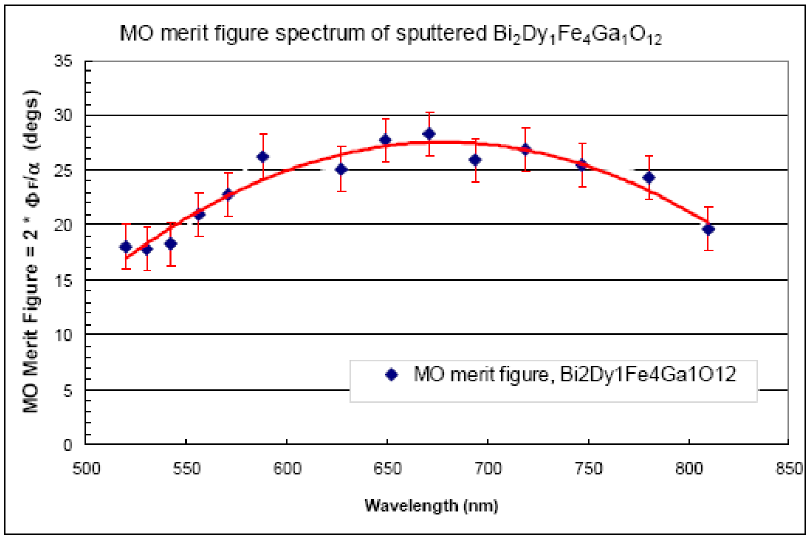


MO characterisation of garnet-phase $(BiDy)_3(FeGa)_5O_{12}$ layers

Combination of optical, magnetic and MO properties achieved in our garnet layers makes them very attractive for use in nanostructured photonic devices and sensors.

Magnetic/MO characterisation of garnet layers





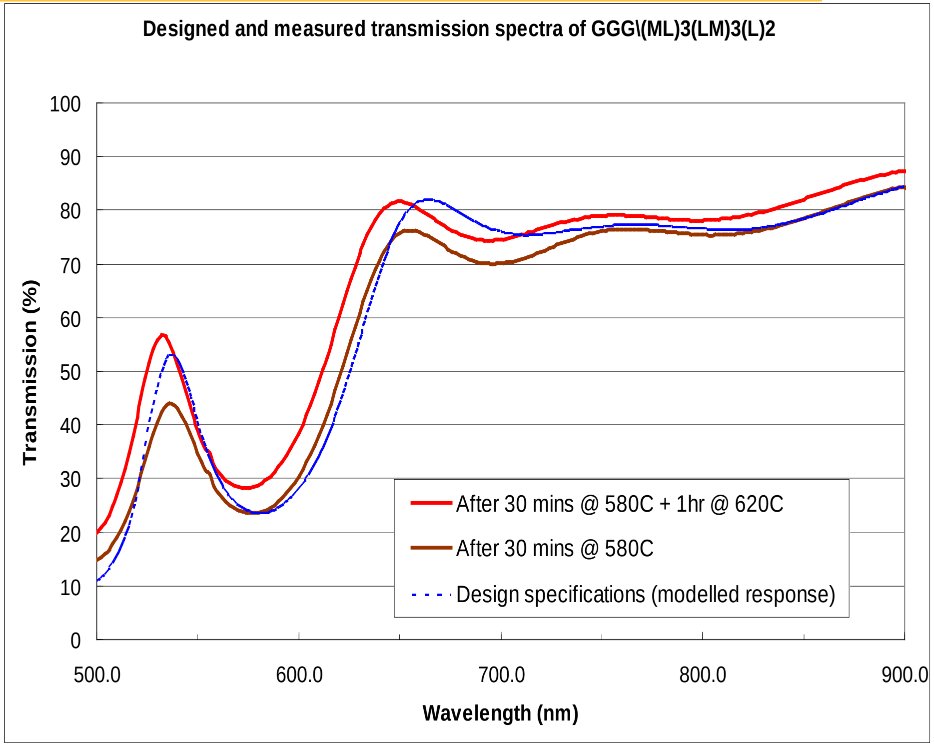
Films with near 100% remnant magnetisation typically result from our deposition/annealing process.

Garnet layers with a "square loop" and high MO quality factors demonstrated

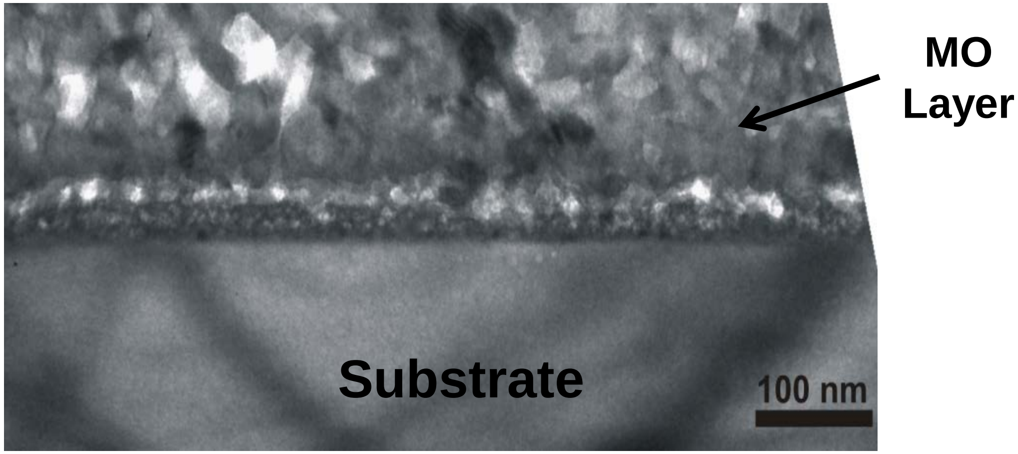
Nano-structure Fabrication

<u>Example:</u> a simple 12-layer all-garnet GGG\GSGG\(Bi,Dy)3(Fe,Ga)5O12 heterostructure designed to enhance Faraday rotation within a transmission peak.

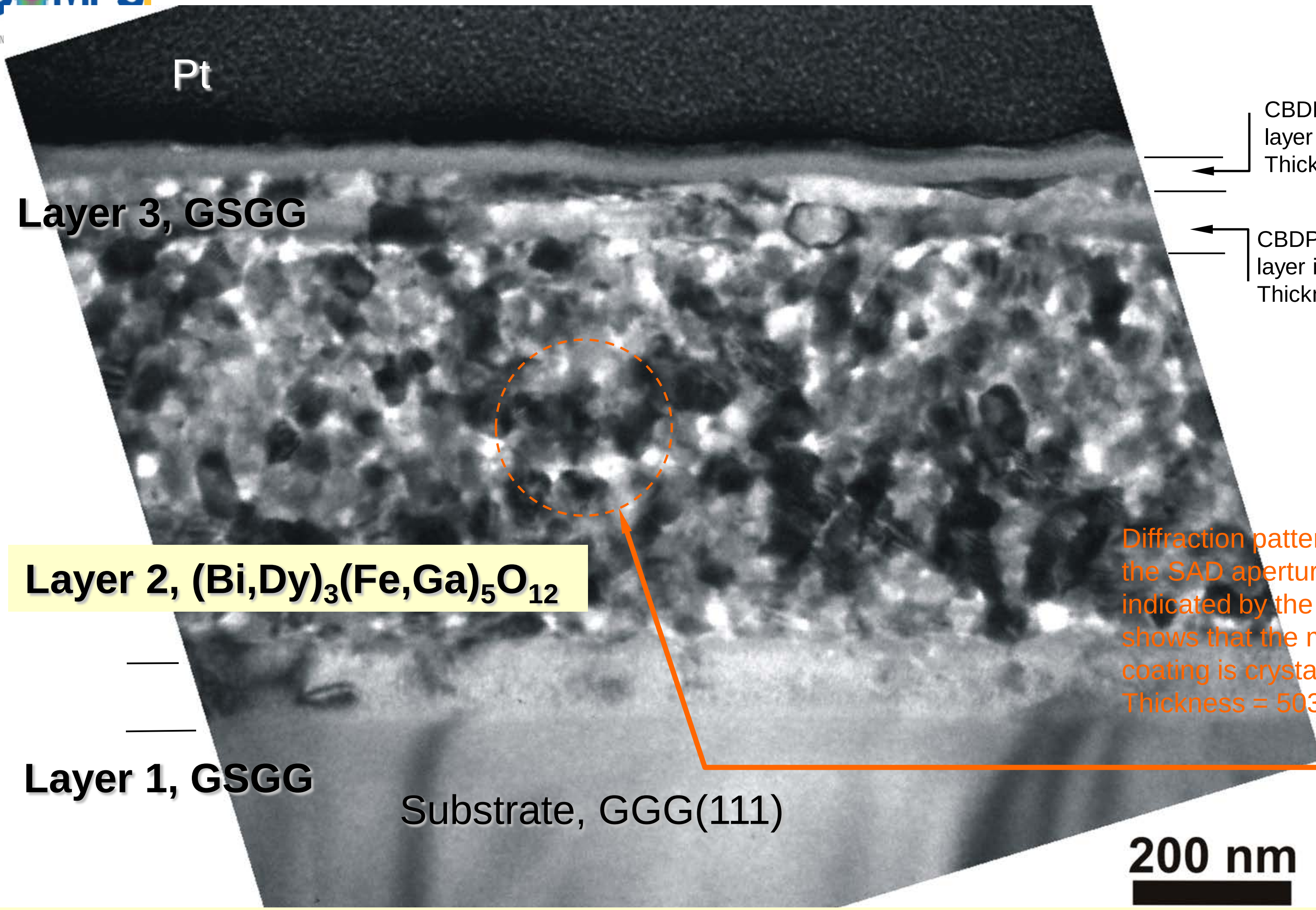
Simultaneous crystallisation achieved within the magnetic and non-magnetic garnet layers, at the same annealing temperature



- Nano-structures perform very well optically (close to design specifications)
- <u>Ongoing development</u>: Improve garnet crystallisation process, microstructure, grain size and magneto-optical performance



TEM characterisation of garnet heterostructures

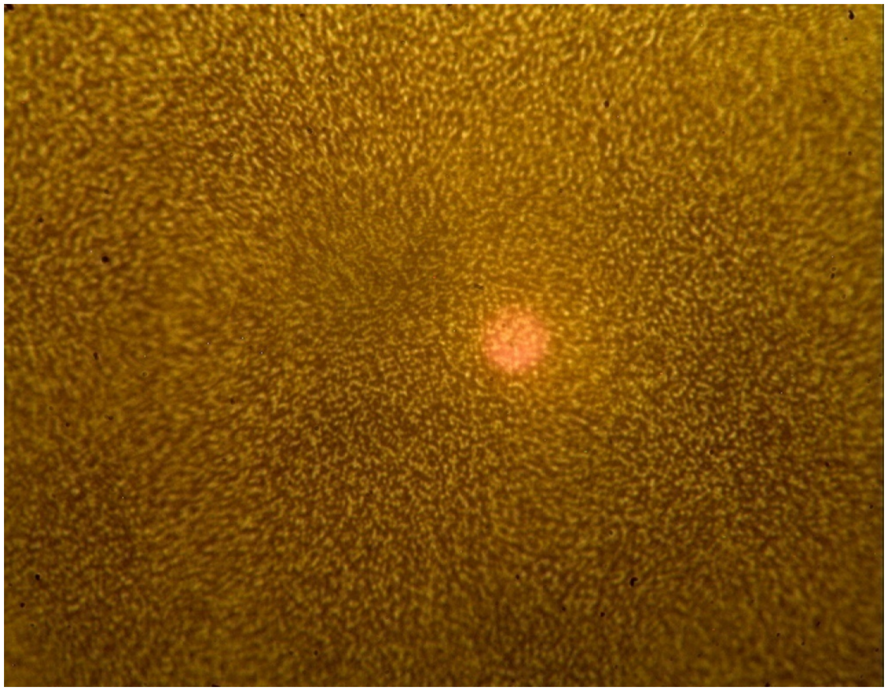


Structure: an all-garnet tri-layer
$Gd_3Sc_2Ga_3O_{12}$, 80nm; $Bi_2Dy_1Fe_4Ga_1O_{12}$, mid-layer, 500 nm; $Gd_3Sc_2Ga_3O_{12}$, top layer, 80 nm. Processing: annealed at 720°C for 2 hrs. Image is courtesy of the Analytical Centre, University of New South Wales, Sydney, NSW, Australia.

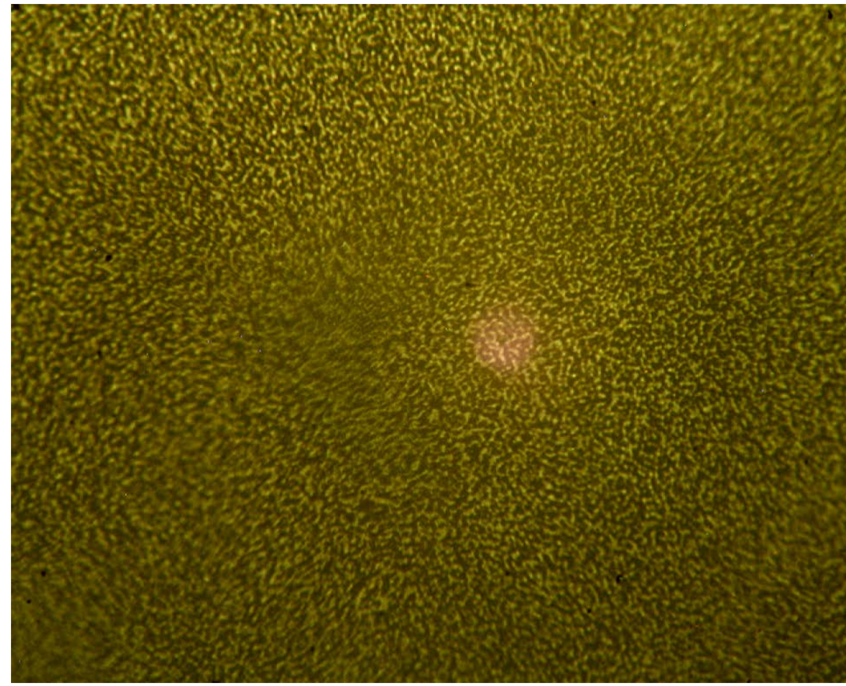
Magnetic domain patterns

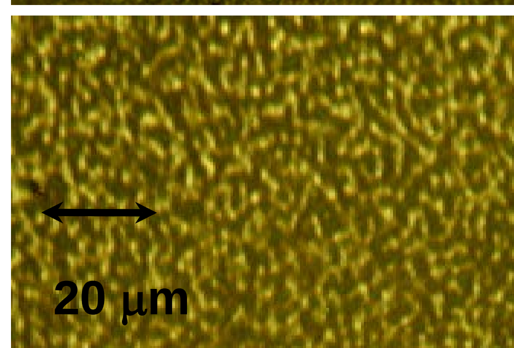
High-quality annealed 14-layer heterostructure sputtered onto GGG(111) substrate

420 µm



X250

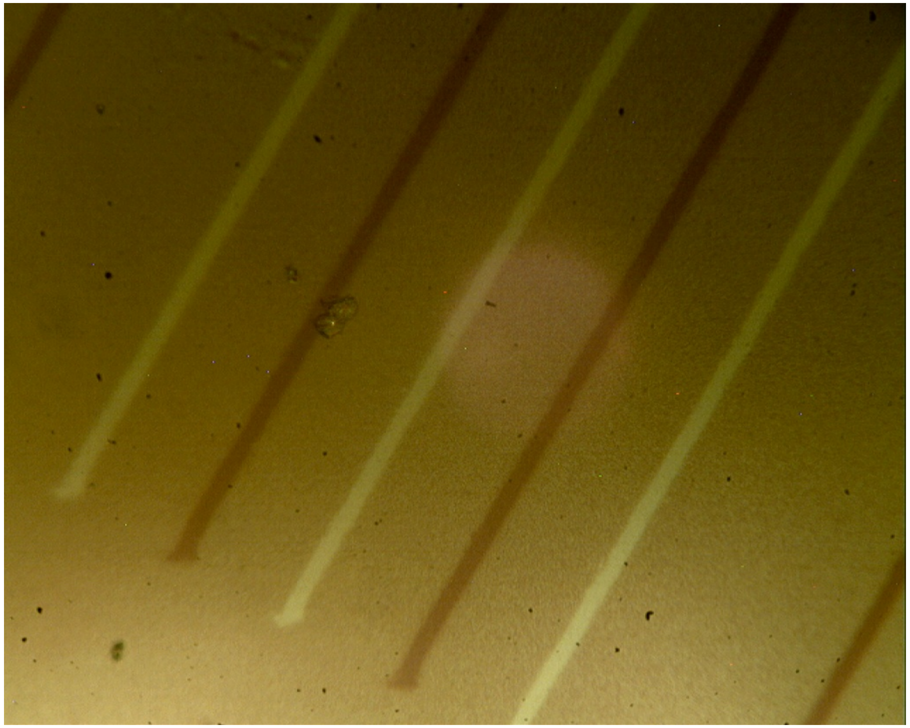




zoomed

Demagnetised 14-layer structure (after 580 C annealing) on GGG substrate shows good MO response.

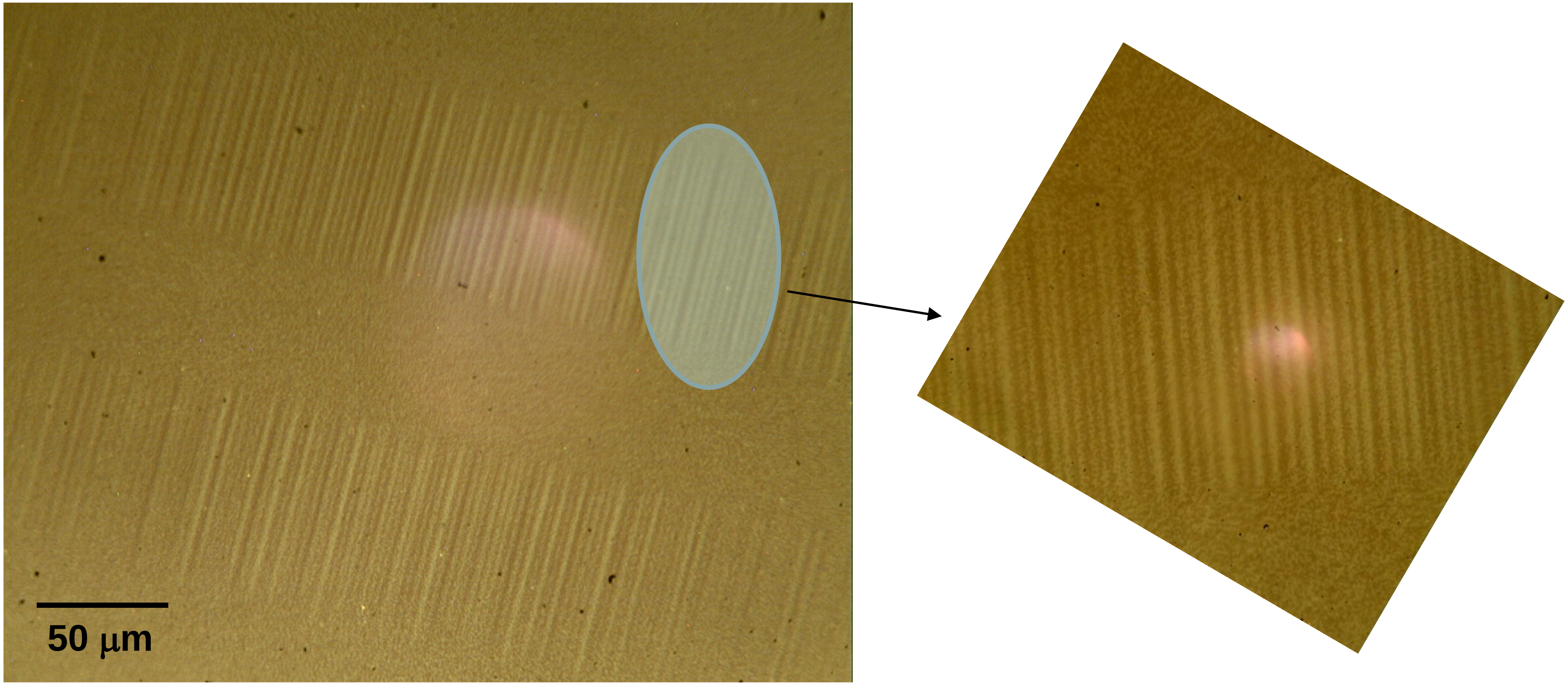
Nano-engineered field visualisers & sensors



- Imaging with 500 nm structure (MO = $Bi_2Dy_1Fe_{4.3}Ga_{0.7}O_{12}$) on GGG, annealed for 1 hr @ 680C
- Imaging of credit card magnetic recording patterns

- Imaging & sensing using nano-structured MO films by examining spatial distribution of magnetic fields produced by magnetized objects
- Digital Forensics - recovery of digital data
- Further nano-structure optimisation enables significant increase in sensitivity

Nano-engineered field visualisers & sensors



- Imaging with 1000 nm structure (MO = $Bi_2Dy_1Fe_{4.3}Ga_{0.7}O_{12}$) on GGG, annealed for 1 hr @ 700C
- Imaging of HD (1.44 Mb) floppy disks recording patterns is possible. Garnet films memorise the images of data patterns after a brief contact with disk surface (provided the domain size is smaller than data feature size).

Advantages of using sputtered MO films with perpendicular magnetic anisotropy

- Most garnet films for MO imaging applications have so far been fabricated with liquid phase epitaxy (LPE).
- LPE limits Bi doping in garnets to a maximum of ~ 1.5 Bi atoms per formula unit
- Most garnet films used for imaging have in-plane magnetisation direction

Advantages of sputtered polycrystalline garnet films include:

- Ability to deposit MO films directly onto objects. This eliminates object/film gap, leading to maximised imagiing resolution. Example application: study of currents flowing in IC conductors.
- Magnetic memory properties – MO images are permanently recorded by touching the objects under study with demagnetised films.
- In perpendicular magnetisation films, it is possible to control magnetic properties by varying layer thicknesses & material composition. Saturated magnetisation can be achieved in external fields ~ 10 Oe $\Rightarrow$ high sensitivity to external fields.
- High Faraday rotations (10's of degs.) achievable with spectrally-optimised nanostructures having multi-level memory -> polarisation control applications.

CONCLUSION

- We have established a set of technologies for deposition and annealing of magneto-optic garnet materials suitable for use in photonic crystal structures.
- 1D Magneto-Photonic Crystal (MPC) structures proposed for Magneto Optic (MO) vizualisers and sensors.
- Significant increase in MPC MO response predicted compared with single-layer films.
- Comprehensive characterisation of the optical, magnetic, and MO properties of (Dy,Ga)-doped iron garnet film layers made by RF sputtering performed.
- Experimentally demonstrated excellent surface quality and very good magnetic and MO properties, ways of further improving microstructure are being investigated using analytical electron microscopy.
- Experimental results & theoretical approach for MPC design will open the way towards practical implementations of high-sensitivity magnetic field sensors and reconfigurable photonic devices, including future integrated polarisation controllers