Dipole-Exchange Spin Waves for Thin Ferromagnetic Films

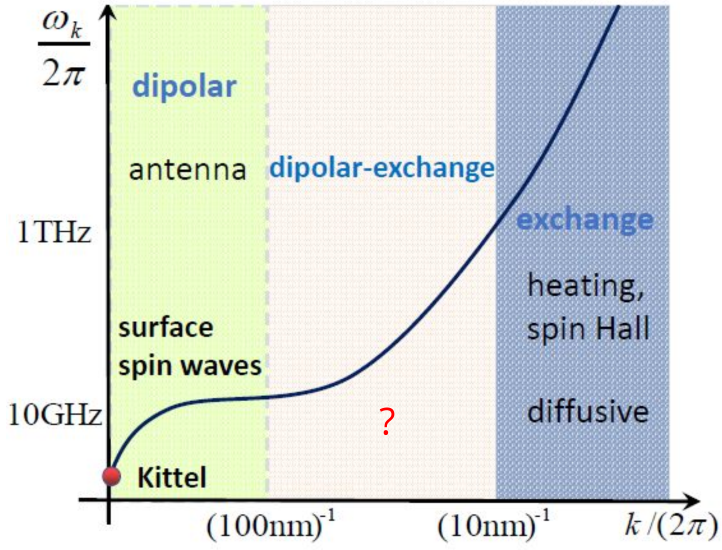
(Under guidance of Sanchar Sharma and Tao Yu)

Introduction

- Surface spin waves (dipole)
    - Chiral i.e. $\vec{k} = \vec{M} \times \vec{n}$
    - Beneficial for magnonic logic devices
    - Exist only in thick magnetic films with small group velocities.
- Exchange waves
    - Non chiral
    - High velocities at higher frequencies
- Dipole-Exchange Spin Waves

This project is to discuss their behavior:

- The magnetization and dipolar field profiles for various modes
- Their chirality for various wave vectors
- Their variation with thickness in thin ferromagnetic films in the transition region



[Tao Yu, a presentation]

Basic Equations

- Landau–Lifshitz equation

$$\frac{d\vec{M}}{dt} = -\gamma\mu_0(\vec{M} \times \vec{H}_{eff})$$

- $$\vec{H}_{eff} = H_{app}\hat{z} + 2\frac{A_{ex}}{\mu_0 M_s^2}\nabla^2\vec{M} + \vec{H}_{dip}$$

[Sanchar Sharma *et al.* Physical Review B99, 214423 (2019)]

  - Applied field: $H_{app}\hat{z}$
  - Exchange term: $2\frac{A_{ex}}{\mu_0 M_s^2}\nabla^2\vec{M}$
  - Dipolar field: $\vec{H}_{dip}$

- If fluctuation in magnetization is small $\vec{m} = me^{-i\omega t}$ we obtain

$$-i\omega m_x = -\gamma\mu_0[H_{app}m_y - M_s h_y - (\frac{M_s}{k_{ex}^2})\nabla^2 m_y]$$

$$-i\omega m_y = -\gamma\mu_0[-H_{app}m_x + M_s h_x + (\frac{M_s}{k_{ex}^2})\nabla^2 m_x]$$

- So, we can solve for magnetization in terms of dipolar field. Let's solve for dipolar field now.

Analytically Solving

$$\nabla \times \vec{H}_{dip} = 0$$
$$\vec{H}_{dip} = H_{demag}\hat{z} + \vec{h}$$

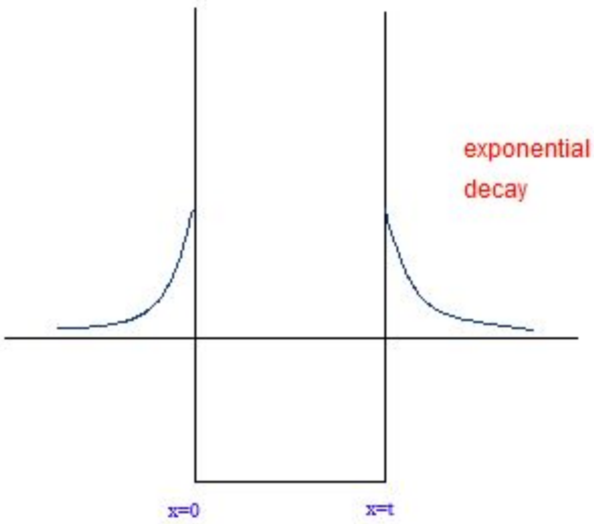
- For the geometry we're considering,

$$H_{demag} = 0$$
$$\vec{H}_{dip} = \vec{h}$$

- Putting $\vec{h} = -\nabla\psi$, in the Maxwell's equation $\nabla.\vec{H}_{dip} = -\nabla.\vec{M}$ we obtain a 6th order complex differential equation.

- Outside the film, we see an exponentially decaying solution.

- Inside the film, we see a solution as:



$$\psi = exp(i(k_y y + k_z z))\sum_{l=1}^{3}[A_l exp(ik_l x) + B_l exp(-ik_l x)]$$

$$-\frac{\Omega_M^2}{k_{ex}^4}K_l^6 - \left(\frac{\Omega_M^2}{k_{ex}^2} + \frac{2\Omega_H\Omega_M}{k_{ex}^2}\right)K_l^4 - \left(\Omega_H\Omega_M - \omega^2 + \Omega_H^2 - \frac{\Omega_M^2}{k_{ex}^2}k_z^2\right)K_l^2 + \Omega_M\Omega_H k_z^2 = 0$$

where

$$K_l^2 = k_l^2 + k_y^2 + k_z^2$$

where k_l^2 are roots of the cubic equation in k_l^2 as specified above and $|\vec{k}| = \sqrt{k_y^2 + k_z^2}$

[R. E. De Wames *and* T. Wolfram, Journal of Applied Physics 41, 987 (1970)]

Boundary Conditions

- continuity of tangential component of $\vec{H}$

$\psi_I|_{x=0} = \psi_{II}|_{x=0}$

$\psi_{II}|_{x=t} = \psi_{III}|_{x=t}$

- continuity of normal component of $\vec{B}$

$$-\frac{\partial \psi_I}{\partial x}|_{x=0} = -\frac{\partial \psi_{II}}{\partial x}|_{x=0} + m_x|_{x=0}$$

$$-\frac{\partial \psi_{III}}{\partial x}|_{x=t} = -\frac{\partial \psi_{II}}{\partial x}|_{x=t} + m_x|_{x=t}$$

- unpinned

$\frac{\partial \vec{m}}{\partial x}|_{surface} = 0$

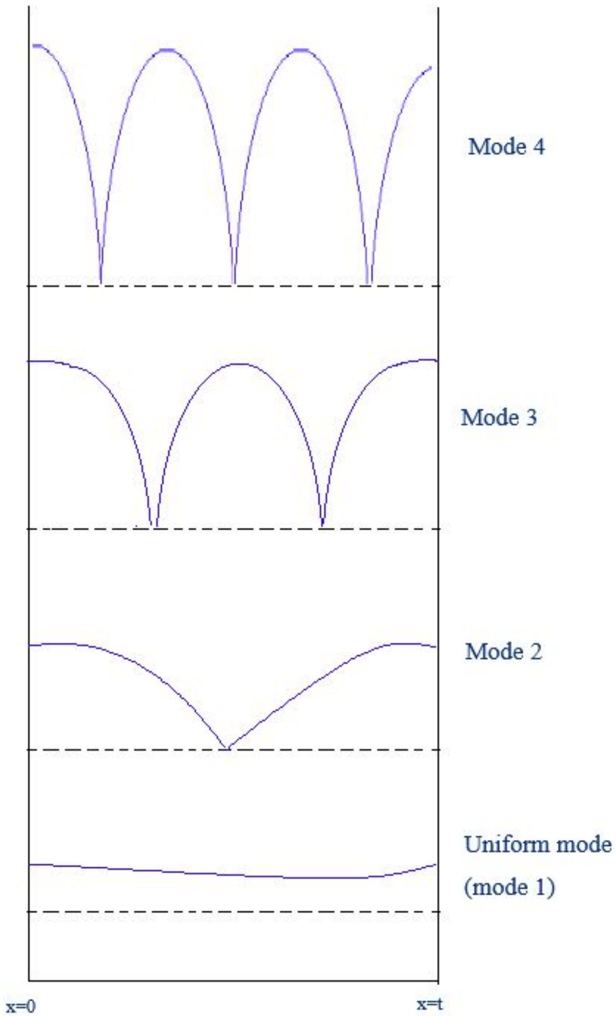
pinned

$\vec{m}|_{surface} = 0$

Numerical Solution

- Even with the boundary conditions being linear in the unknown constant coefficients, it becomes too complicated to solve analytically.
- We obtain a 6x6 matrix as a complex function of ω, k_y, k_z.
- Solve it numerically using MATLAB code which can
  - Find dispersion (ω-k_y) relation
  - Automatically find magnetization modes for a given wave vector and film thickness
  - Obtain dipolar field for different modes

Modes of Magnetization



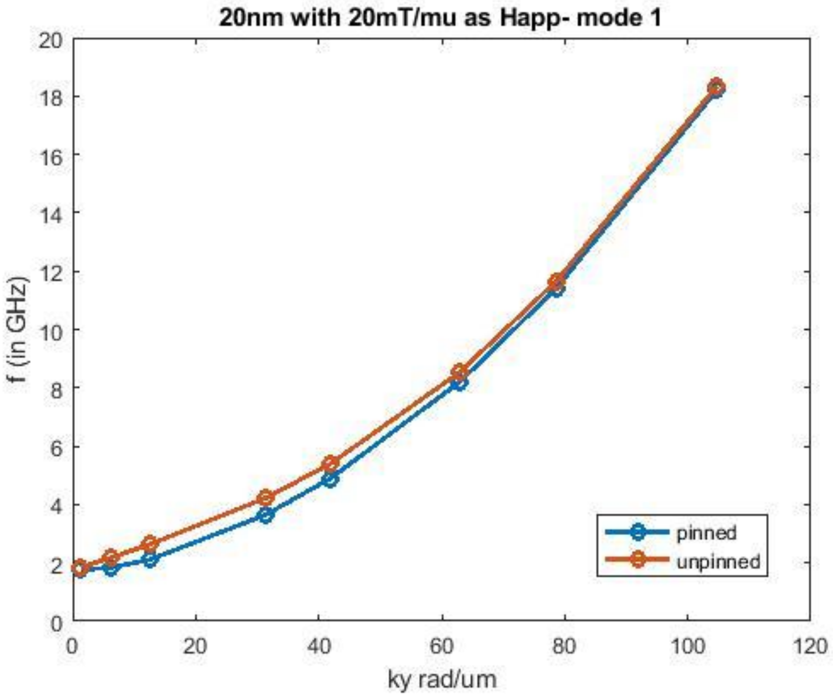
Absolute value of magnetisation

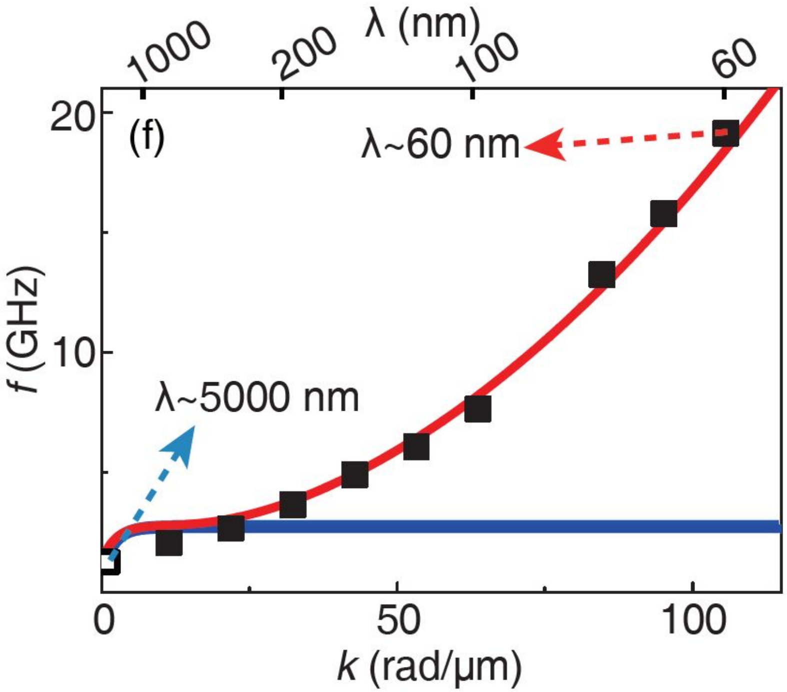
- Thin films (10-300 nm approx)
    - Non-trivial uniform mode is first mode
    - After that, modes with nodes in the film
- Thick films (>300 nm)
    - No uniform mode is obtained
    - First mode is mode 2 as shown

Note: The film extends infinitely in Y and Z directions, with thickness ‘t’ in X direction, with applied field in Z direction.

Figure for demonstration, not to scale

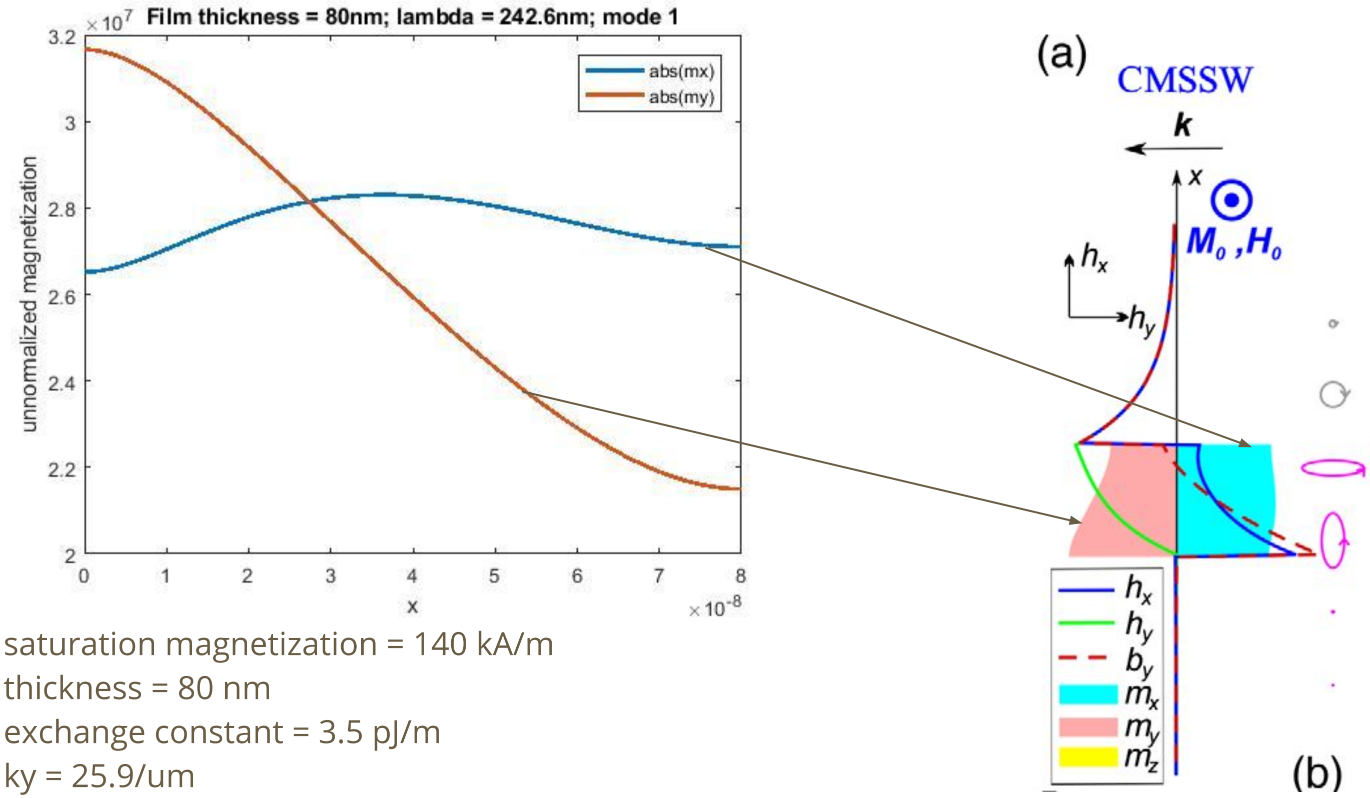
Code check: ω-k_y Plot for 20 nm film when k_z=0





[Jilei Chen *et al.* arXiv:1903.00638]

Code Check: Magnetization in the film when k_z=0



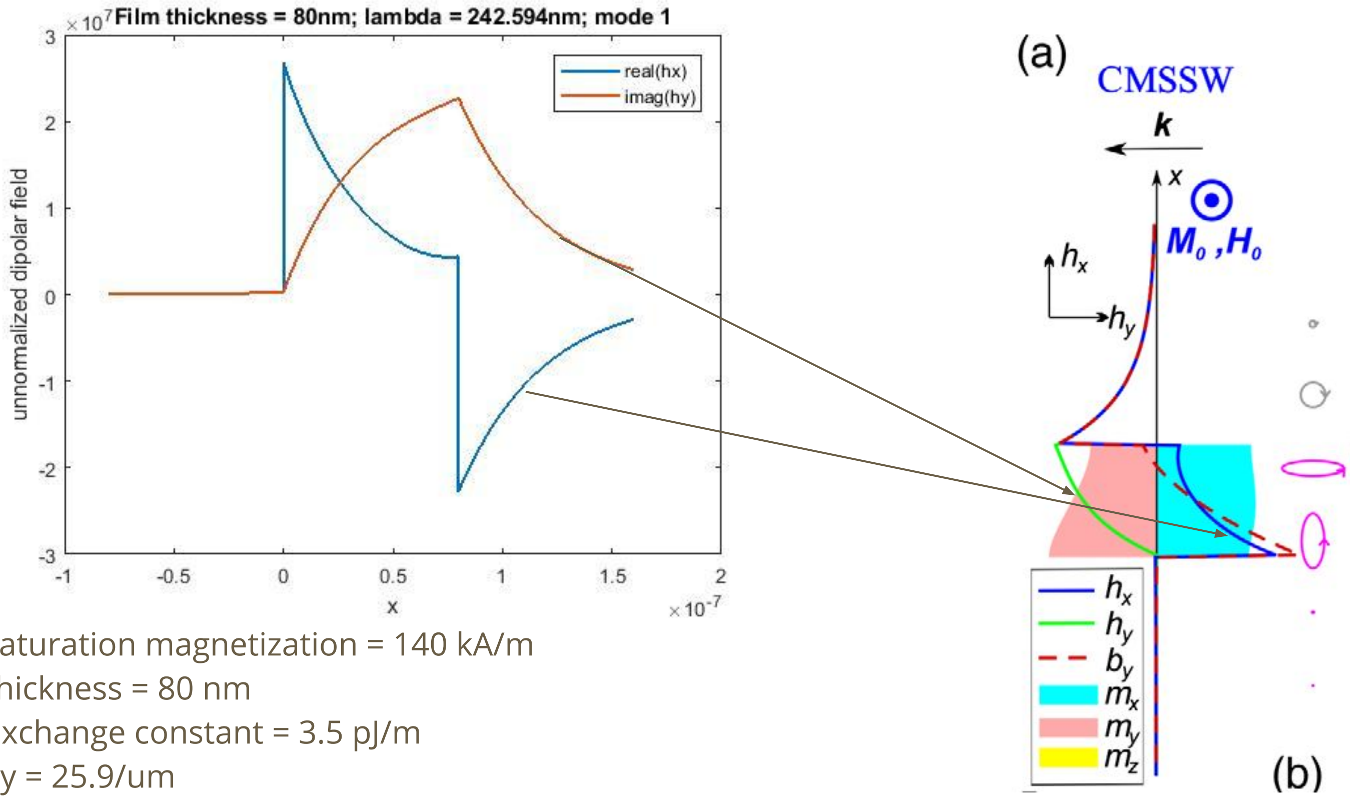
- saturation magnetization = 140 kA/m
- thickness = 80 nm
- exchange constant = 3.5 pJ/m
- ky = 25.9/um
- applied field as 0.187/mu (H_{app} wasn't specified)

[M. Mohseni *et al.* Physical Review Letters 122, 197201 (2019)]

Magnetization profile obtained is similar.

Ellipticity is notable.

Code Check: Dipolar Field in the film when k_z=0



- saturation magnetization = 140 kA/m
- thickness = 80 nm
- exchange constant = 3.5 pJ/m
- ky = 25.9/um
- applied field as 0.187/mu (H_{app} wasn't specified)

[M. Mohseni *et al.* Physical Review Letters 122, 197201 (2019)]

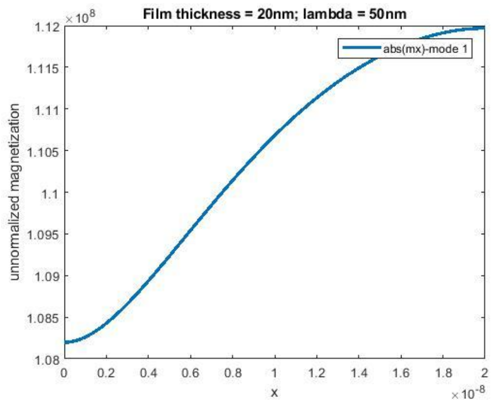
Dipolar field profile obtained is similar.

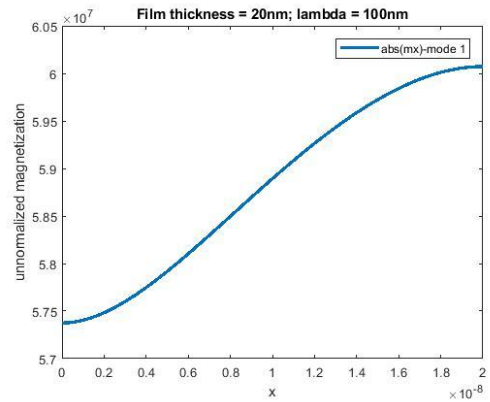
20 nm thickness film

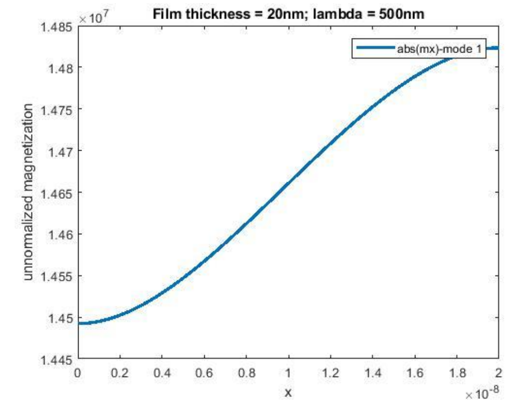
Magnetization when k_z=0 for a 20 nm film

Comparing the first mode for different values of $\lambda = 2\pi/k_y$. Can see uniform almost by scale

m_x





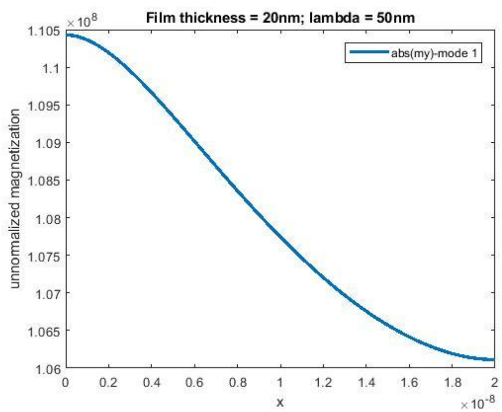


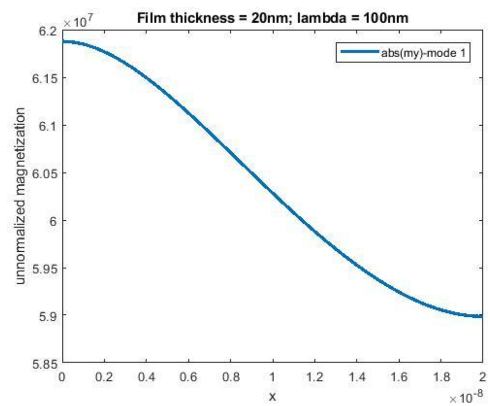
λ=50 nm

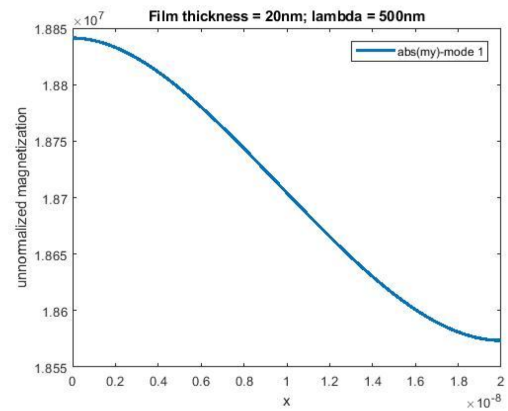
λ=100 nm

λ=500 nm

m_y



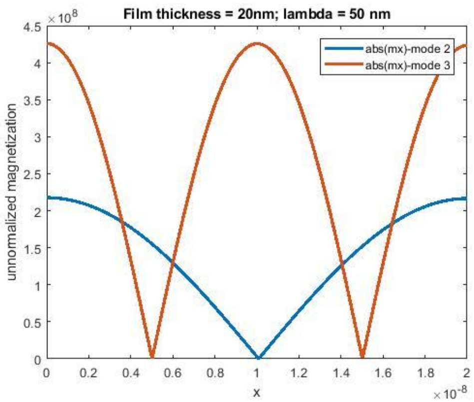




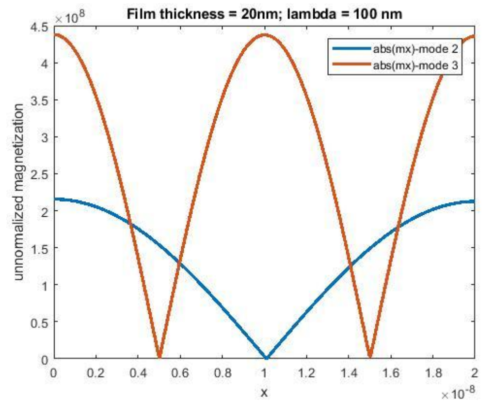
Magnetization when k_z=0 for a 20 nm film

Comparing the second and third modes for different values of $\lambda = 2\pi/k_y$ we see no chirality.
These modes occur on k_x = thickness/pi and 2*thickness/pi, k_x being the real root.

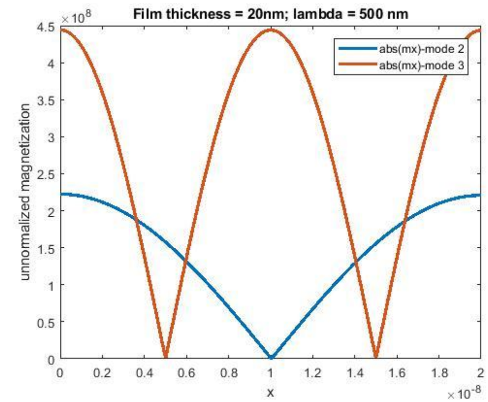
m_x



λ=50 nm

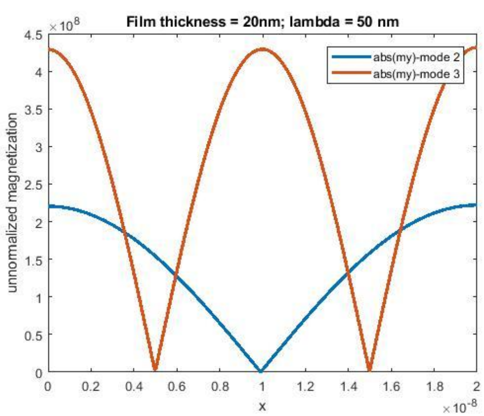


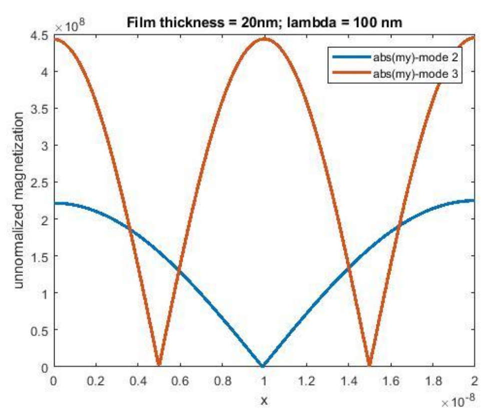
λ=100 nm

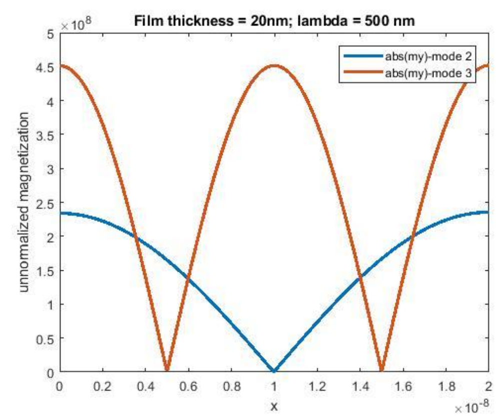


λ=500 nm

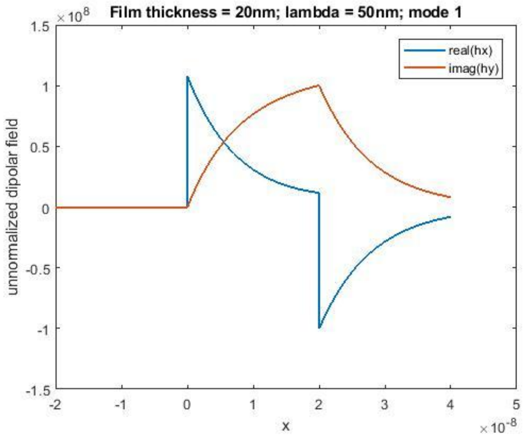
m_y



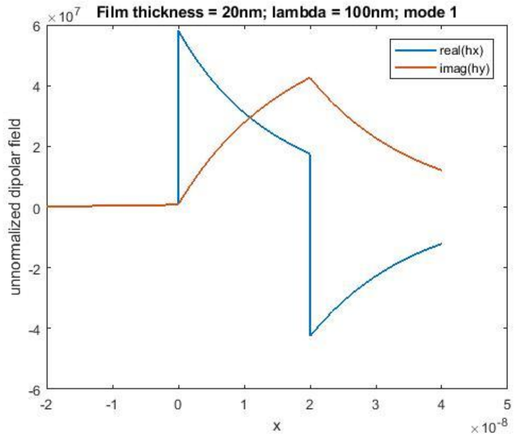




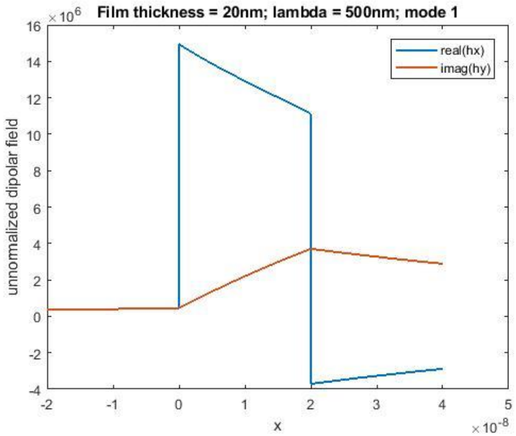
Dipolar field when k_z=0 for a 20 nm film (x = 0 to 20)



λ=50 nm



λ=100 nm



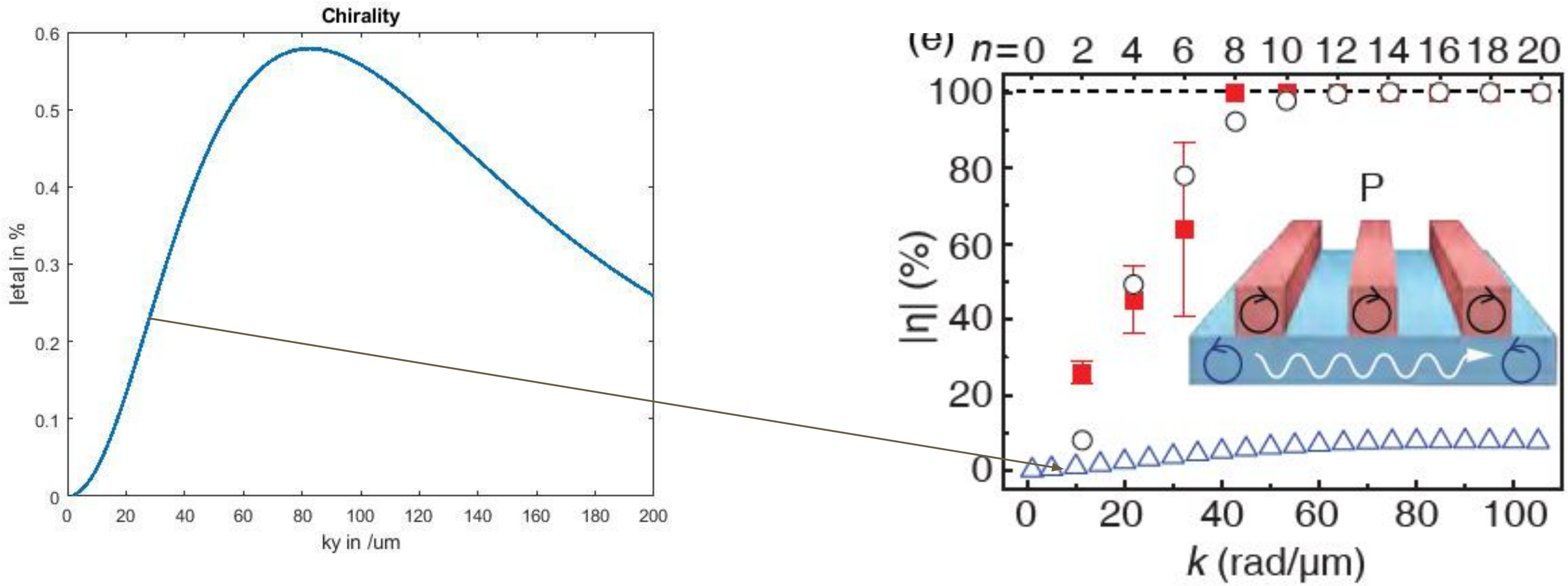
λ=500 nm

We can see that the dipolar field is chiral.

Chirality

Defining chirality as $$\eta = \frac{|m_k|^4 - |m_{-k}|^4}{|m_k|^4 + |m_{-k}|^4}$$

where k is the wave vector and $|m_k|^2 = |m_x|^2_{x=t} + |m_y|^2_{x=t}$

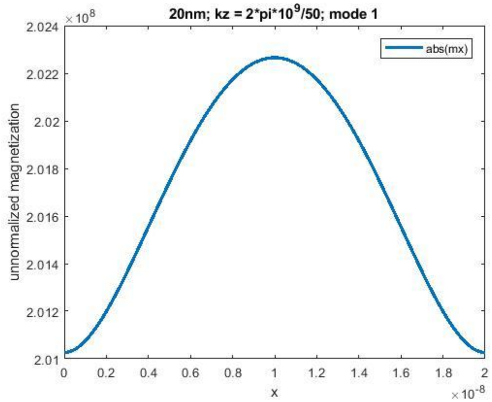


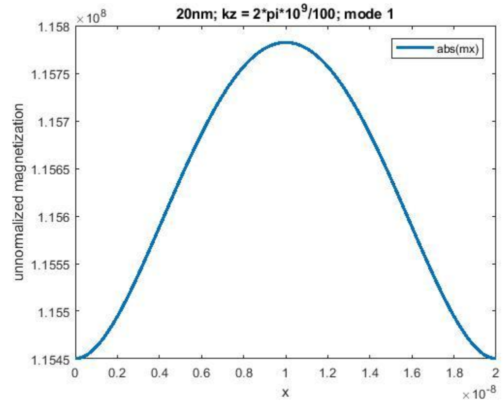
[Jilei Chen *et al.* arXiv:1903.00638]

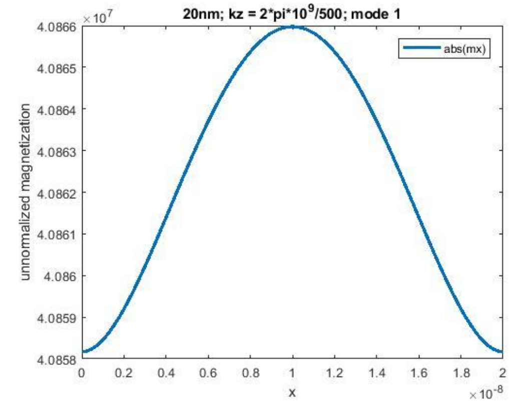
Magnetization when k_y=0 for a 20 nm film

Comparing the first mode for different values of $\lambda = 2\pi/k_z$

m_x





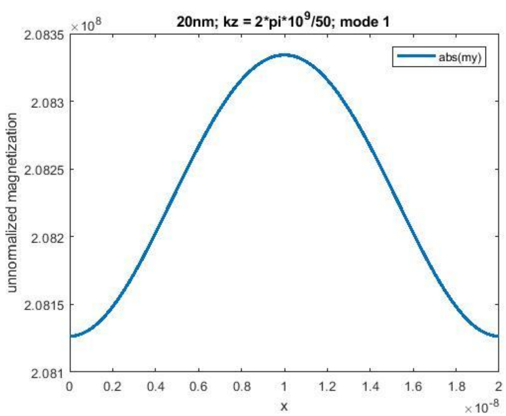


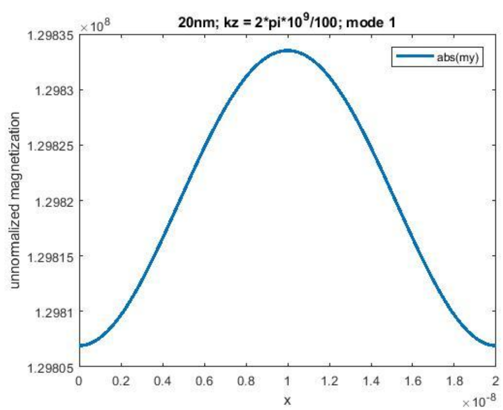
λ=50 nm

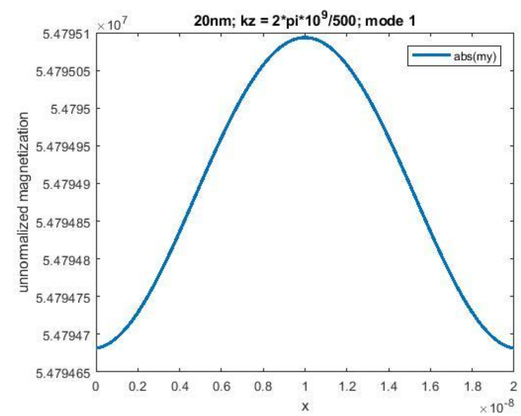
λ=100 nm

λ=500 nm

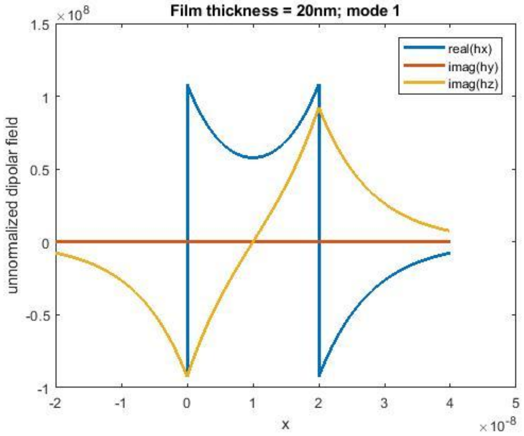
m_y



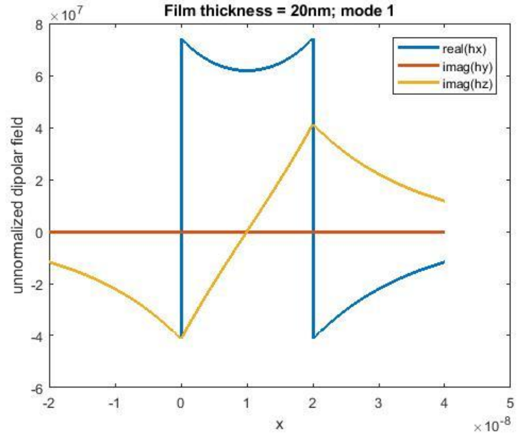




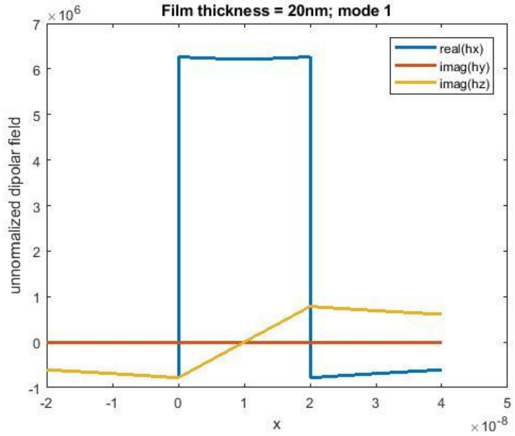
Dipolar field when k_y=0 for a 20 nm film (x = 0 to 20)



λ=50 nm



λ=100 nm



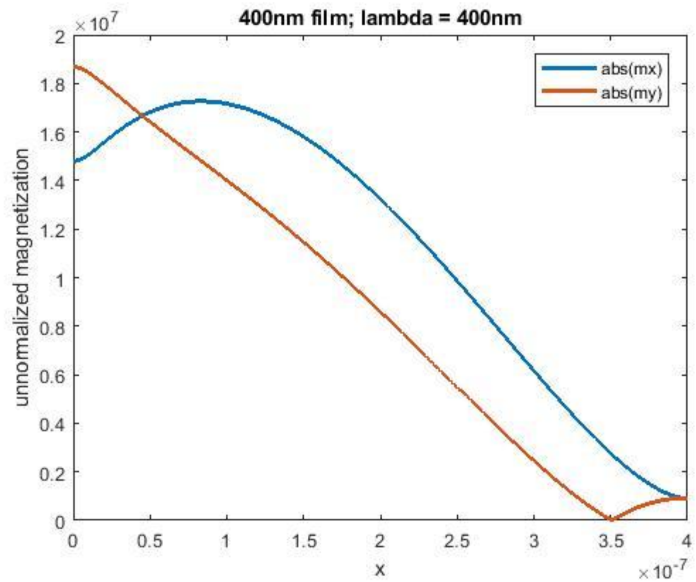
λ=500 nm

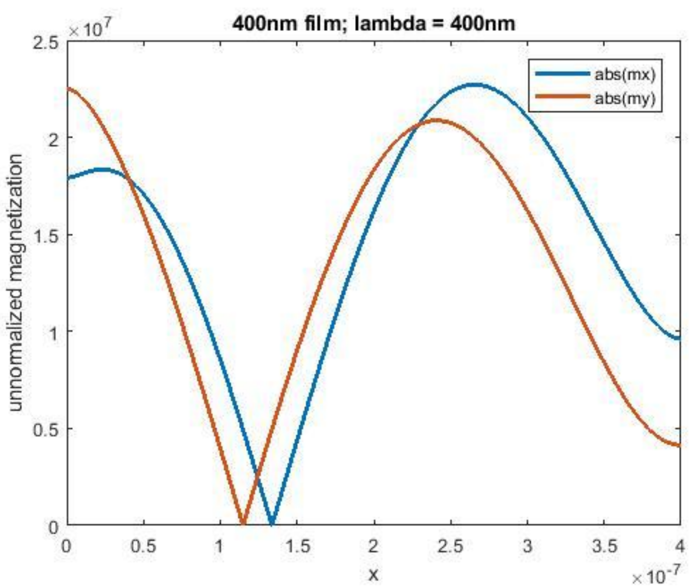
We can see that here dipolar field in x direction is not chiral.
In fact, $h_x = ih_z$ for $x > t$ and $h_x = -ih_z$ for $x < 0$.

Thicker films

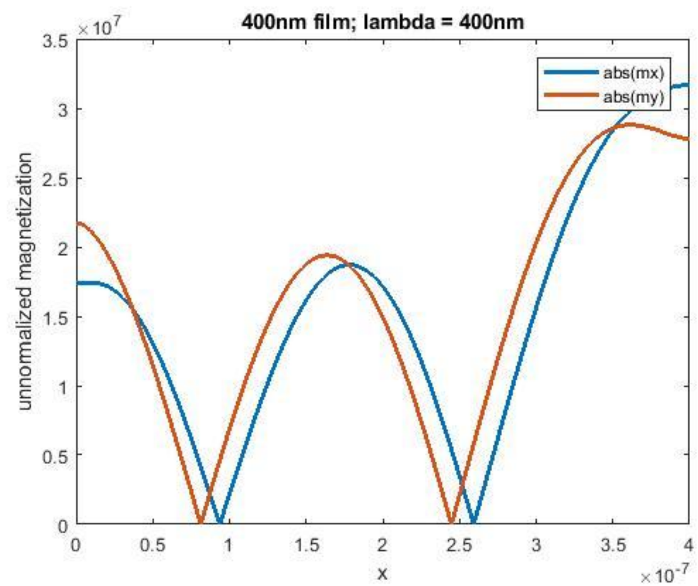
Chirality when k_z=0 for a 400 nm film at higher lambda

- No uniform mode as expected
- Chirality decreases for the next modes



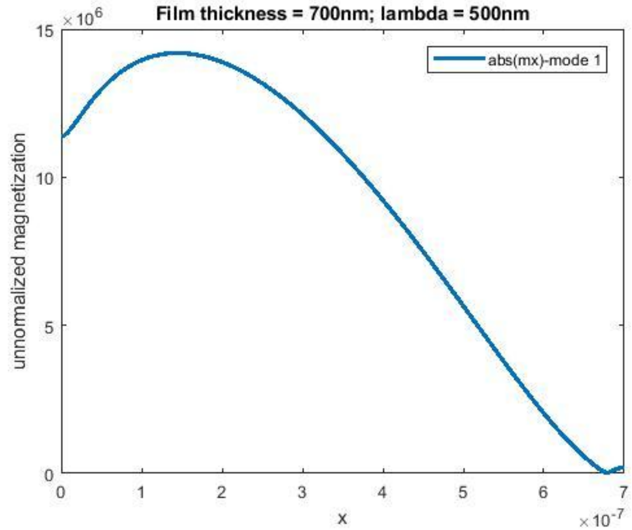


λ=400nm

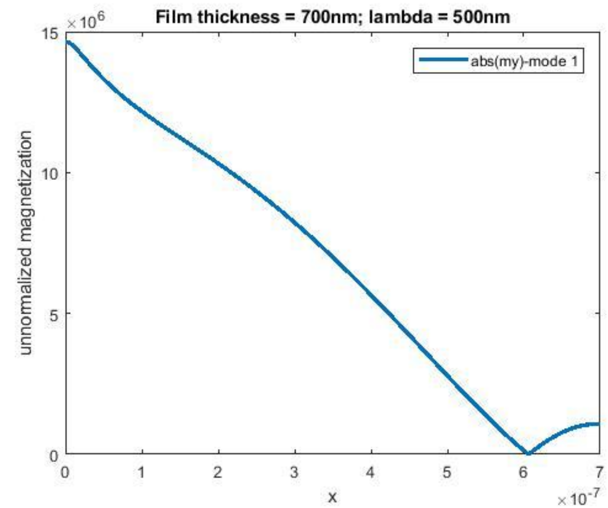


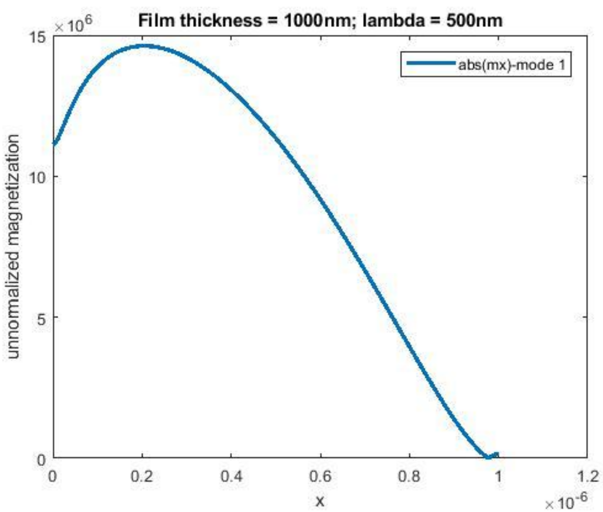
Magnetization distribution independent of thickness

m_x m_y

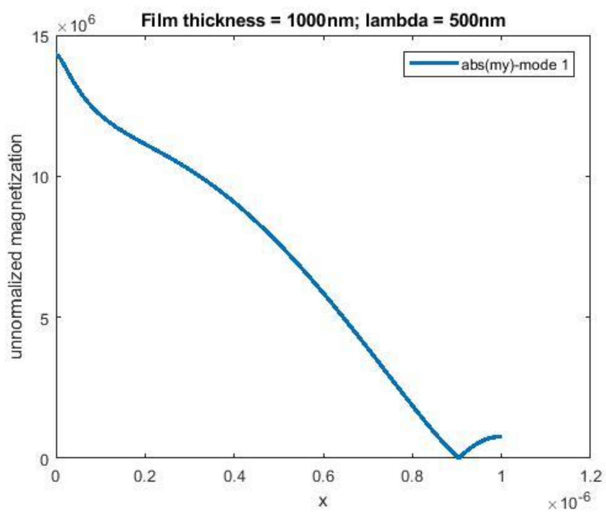


t=700 nm
λ=500 nm



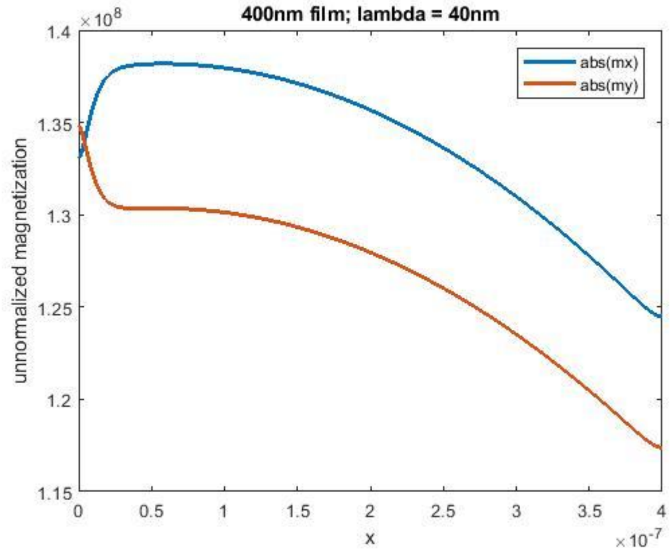


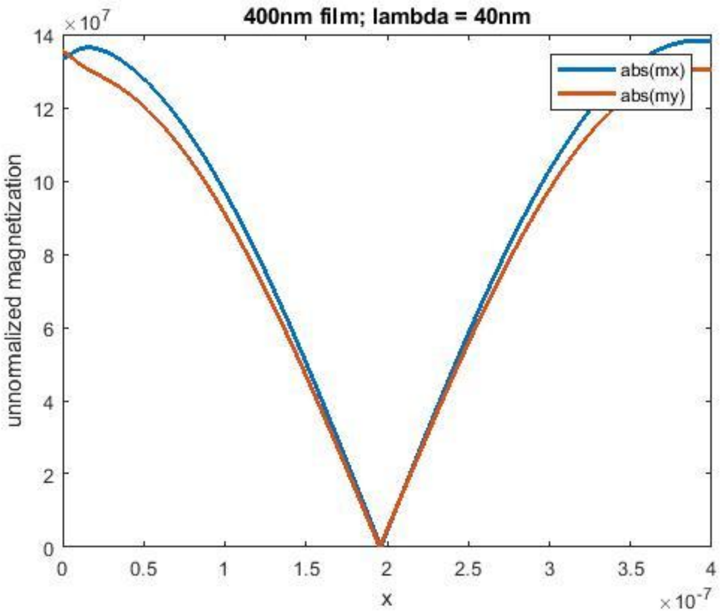
t=1000 nm
λ=500 nm



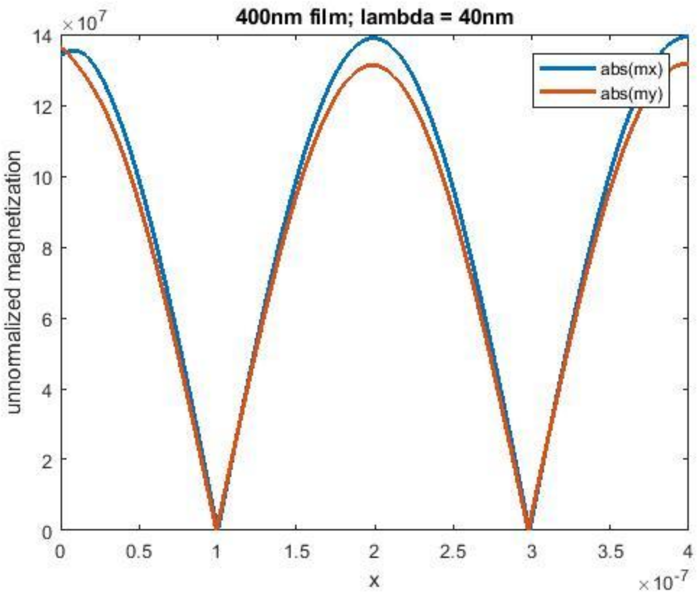
No chirality when k_z=0 for a 400 nm film at lower lambda

- Uniform mode is seen
- No chirality for the next modes



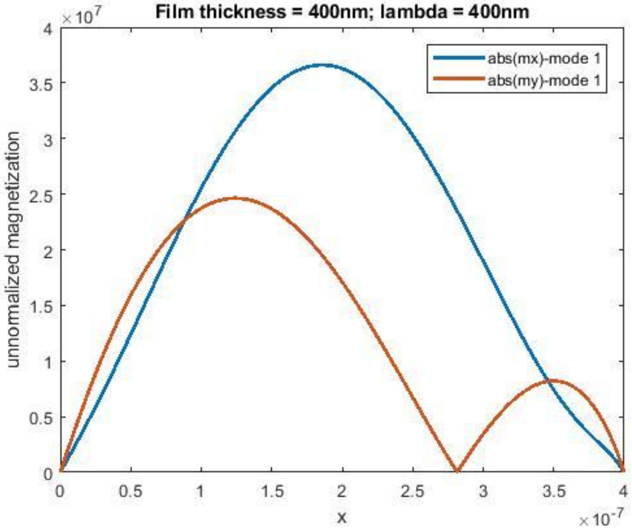


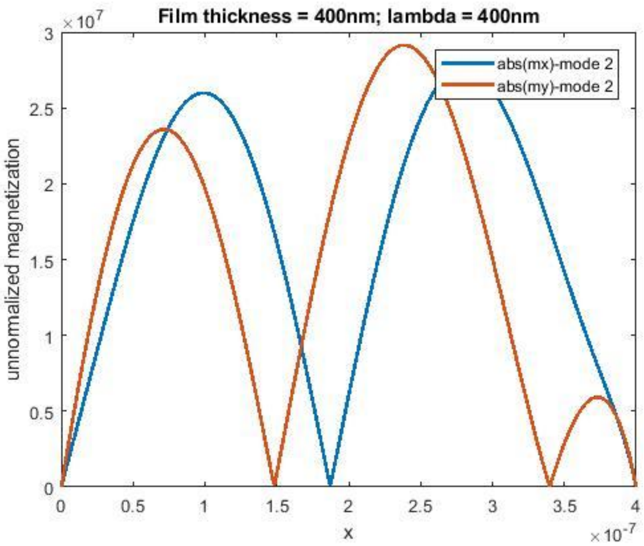
λ=40nm



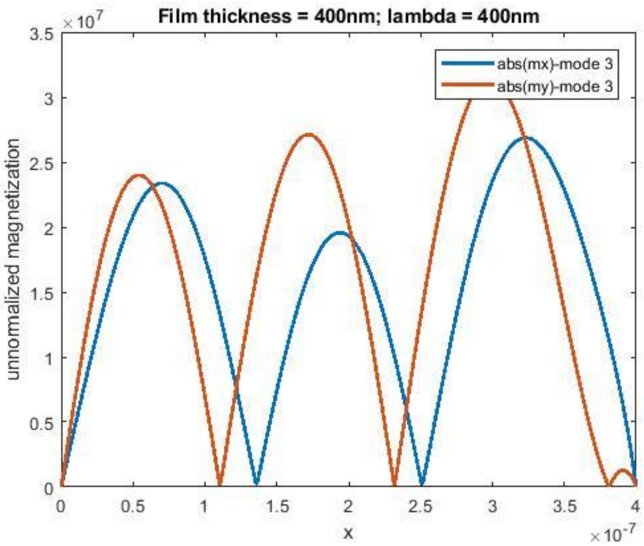
Chirality when k_z=0 for a 400 nm film at higher lambda (Pinned Boundary)

- No uniform mode as expected

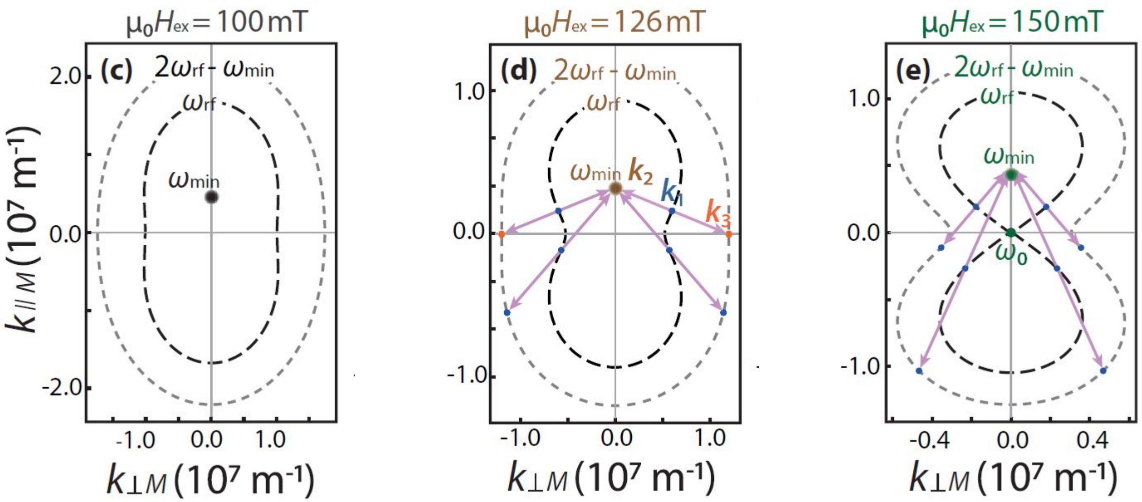


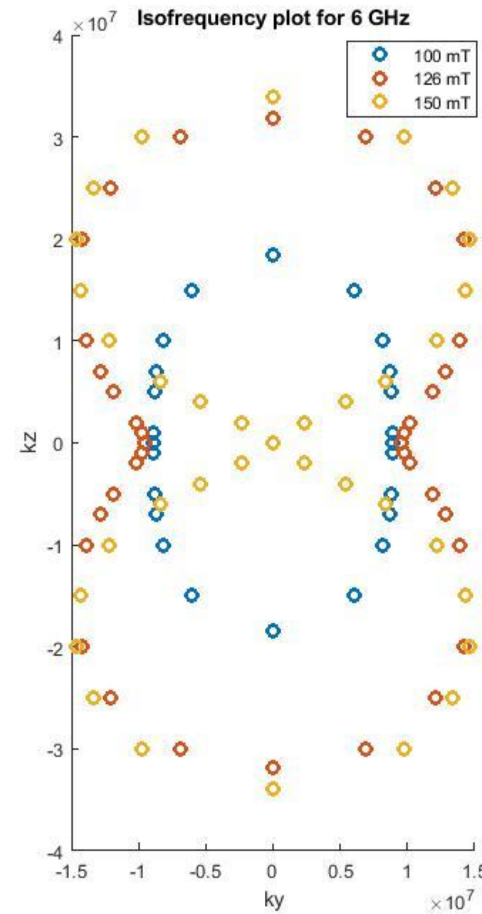


λ=400 nm

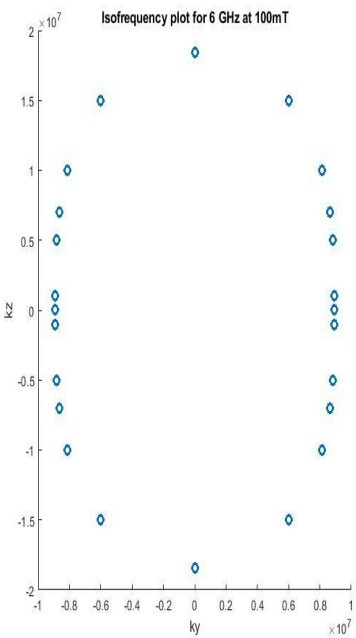


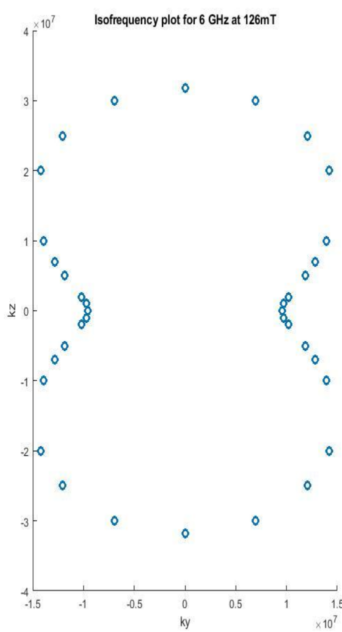
Isofrequency Curve for ω/2π = 6 GHz

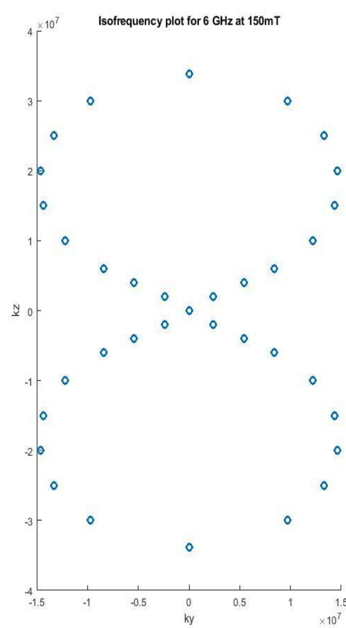




[J. Liu *et al.* Physical Review B 99, 054420 (2019)]







210-nm-thick YIG

γ = 27.3 GHz/T

$\mu_0 M_s$ = 170 mT

A_{ex} = 3.5x10^{-12}

Conclusion

- Chirality in magnetization isn't seen in very thin 20 nm films, but x component of dipolar field is chiral for $k_z = 0$. For $k_y = 0$, even that loses chirality.
- For thin films, the modes after uniform mode occur on kx being an integral multiple of (thickness/pi)
- In thick (400 nm - 1000 nm) films, chirality in magnetization is seen, although no uniform mode is obtained.

References

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- Non-reciprocity of dipole-exchange spin waves in thin ferromagnetic films - M. Kostylev
- Optimal mode matching in cavity optomagnonics - Sanchar Sharma, Babak Zare Rameshti, Yaroslav M. Blanter, Gerrit E. W. Bauer
- Microwave control of thermal-magnon spin transport - J. Liu, F. Feringa, B. Flebus, L. J. Cornelissen, J. C. Leutenantsmeyer, R. A. Duine, B. J. van Wees
- Excitation of unidirectional exchange spin waves by a nanoscale magnetic grating - Jilei Chen, Tao Yu, Chuanpu Liu, Tao Liu, Marco Madami, Ka Shen, Jianyu Zhang, Sa Tu, Md Shah Alam, Ke Xia, Mingzhong Wu, Gianluca Gubbiotti, Yaroslav M. Blanter, Gerrit E. W. Bauer and Haiming Yu
- Backscattering Immunity of Dipole-Exchange Magnetostatic Surface Spin Waves - M. Mohseni, R. Verba, T. Brächer, Q. Wang, D. A. Bozhko, B. Hillebrands, P. Pirro