NanoMagnetism

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Support

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Support

➢**Supported by the DOE, Basic Energy Sciences.**

Scope of Research

- Micromagnetics
- Spin polarized transport
- Magnetic photonic crystals.
- Small wire structures and their magneto- electric properties.

Paper published

- (1) Magnetic resonances in metallic double split rings: lower frequency limit and bi-anisotropy, L. Zhou and S. T. Chui, Appl. Phys. Lett. 94, 041903 (2007).
- (2) Manipulating electromagnetic radiation with magnetic photonic crystals, Z. F. Lin and S. T. Chui, Optics Letters, 32, 2288 (2007).
- (3) Probing states with macroscopic circulations in magnetic photonic crystals , Chui ST, Lin ZF, JOURNAL OF PHYSICS-CONDENSED MATTER 19 (40), 406233, (2007).
- (4) Large voltage from spin pumping in magnetic tunnel junctions, Chui ST, Lin ZF, PHYSICAL REVIEW B 77 , 094432 (2008).
- (5) Design and miniaturization of split ring structures based on an analytic solution of their resonance, S. T. Chui, Y. Zhang, and L. Zhou, J. Appl. Phys. 104, 034305 (2008).
- (6) Electric and magnetic resonances in broadside coupled split-ring resonators: An extended mode-expansion theory, Huang XQ, Zhang Y, Chui ST, and L. Zhou, PHYSICAL REVIEW B 77, 235105 (2008) .
- (7) Magnetic resonance of slotted circular cylinder resonators, Du JJ, Liu SY, Lin ZF, and S. T. Chui, JOURNAL OF APPLIED PHYSICS, 104 , 014907 (2008).
- (8) Giant wave rotation for small helical structures, Jour. Appl. Phys. 104, 013904 (2008).
- (9) Molding the flow of electromagnetic waves and creating a mirage with a magnetic field, Shaowen Chen, Junjie Du, Shiyang Liu, Zhifang Lin, and S. T. Chui, Phys. Rev. A 78, 043803 (2008).
- (10) Manipulating negative refracting behavior with a magnetic field, Shiyang Liu, Weikang Chen, Junjie Du, Zhifang Lin, S. T. Chui and C. T. Chan, Phys. Rev. Lett., 101, 157407, (2008).
- (11) Long-wavelength behavior of two-dimensional photonic crystals, Chui ST, Lin ZF, PHYSICAL REVIEW E , 78 , 065601 (2008)
- (12) Focusing the electromagnetic wave with a magnetic field, Chen S, Du J, Liu S, Z. F. Lin and S. T. Chui, OPTICS LETTERS 33, 2476-2478 (2008) .
- (13) Formation of robust and completely tunable resonant photonic band gaps, Liu SY, Du JJ, Lin ZF, R. Wu and S. T. Chui, PHYSICAL REVIEW B 78 , 155101 (2008)
- (14) Longitudinal elliptically polarized electromagnetic waves in off-diagonal magnetoelectric split ring composites, S. T. Chui, Weihua Wang, L. Zhou and Z. F. Lin, Jour. Phys. Conds. Matt. 21 (2009) 292202
  (15)Effective-medium properties of metamaterials: A quasimode theory, Shulin Sun, S. T. Chui, and Lei Zhou, Phys. Rev. E 79, 066604 (2009)
  (16) Guiding electromagnetic energy below the diffraction limit with dielectric particle arrays, Junjie Du, Shiyang Liu, Zhifang Lin, Jian Zi, and S. T. Chui, Phys. Rev. A 79, 051801 (2009).
- (17) A generalized equivalent circuit theory for the electric and magnetic resonances of metallic wire networks Weiyi Zhang and S. T. Chui, J. Appl. Phys. 105 113121 (2009) .

Outline

- **Magnetic photonic crystals.**
- **A.C. circuit theory for wire structures.**

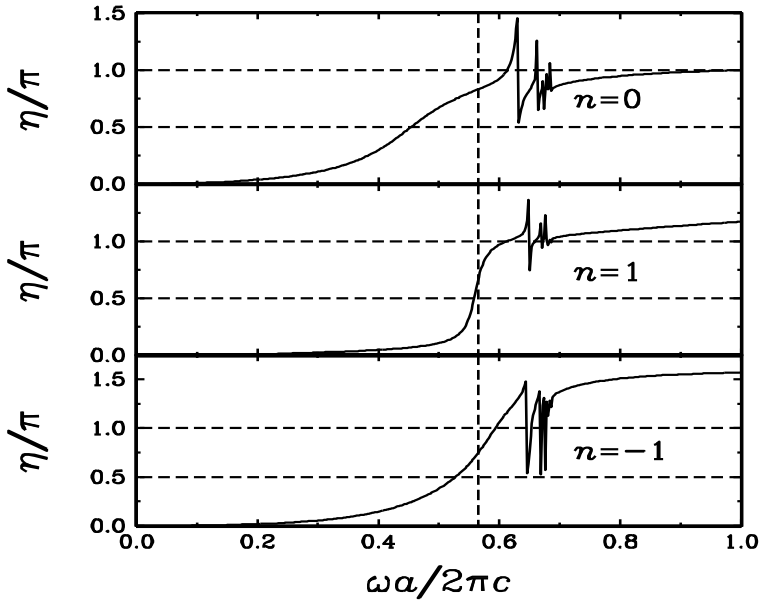
Magnetic Photonic Crystal (MPC)

- **Yin-Yang reflection: Analog of the Quantized Hall Effect, mediated by magnetic surface plasmon states**
- **Magnetic surface plasmon bands: Tuning of the photonic band.**
- **Pseudopotential: Index matched negative refraction with no metallic wires.**

Electromagnetic (EM) scattering phase shift between magnetic and nonmagnetic cylinders are different.

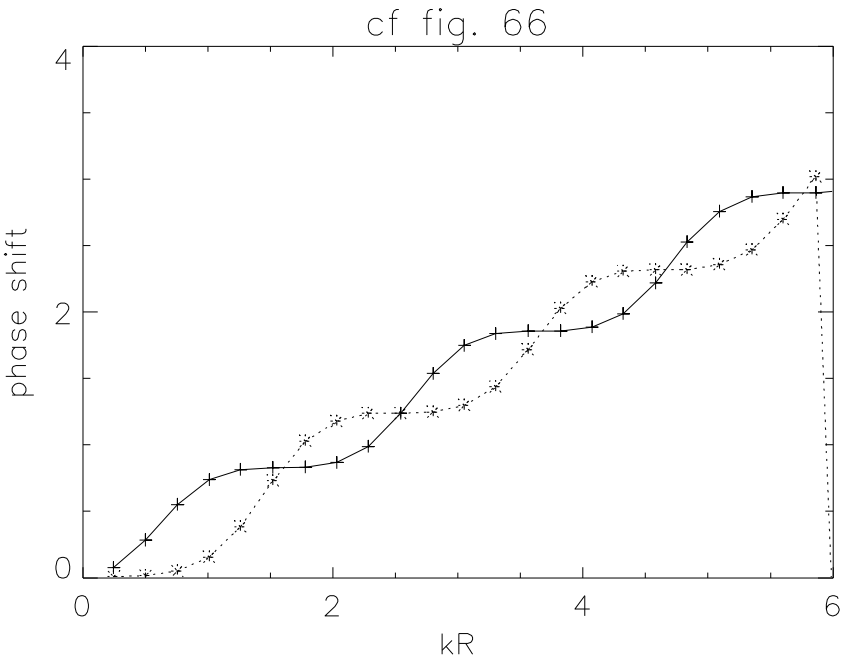
Rapidly changing scattering phase shift off a magnetic cylinder

- In the middle panel, at the dashed line, phase shift η_1 for angular momentum n=1 is near the resonance value of $\pi/2$ and is rapidly changing.
- $\eta_{-1} \neq \eta_1$



Scattering phase shift from a nonmagnetic cylinder

- **No rapid oscillation of phase shift is observed for nonmagnetic cylinders.**

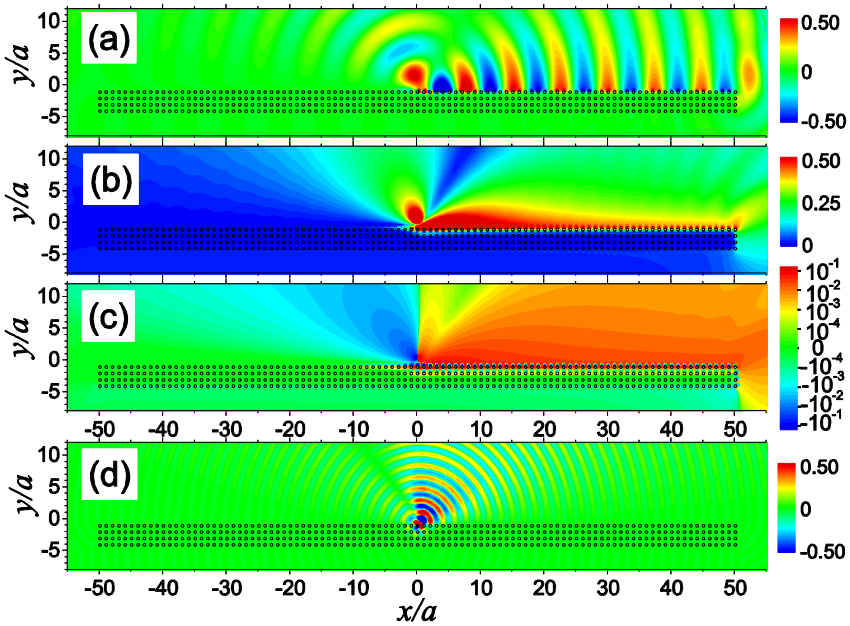


Yin Yang Reflection: Tunable "one-way" subwavelength waveguide with superflow properties

Quantized Hall effect and magnetic-plasmonics: [JPCM 19, 406233 (2007) and unpublished]

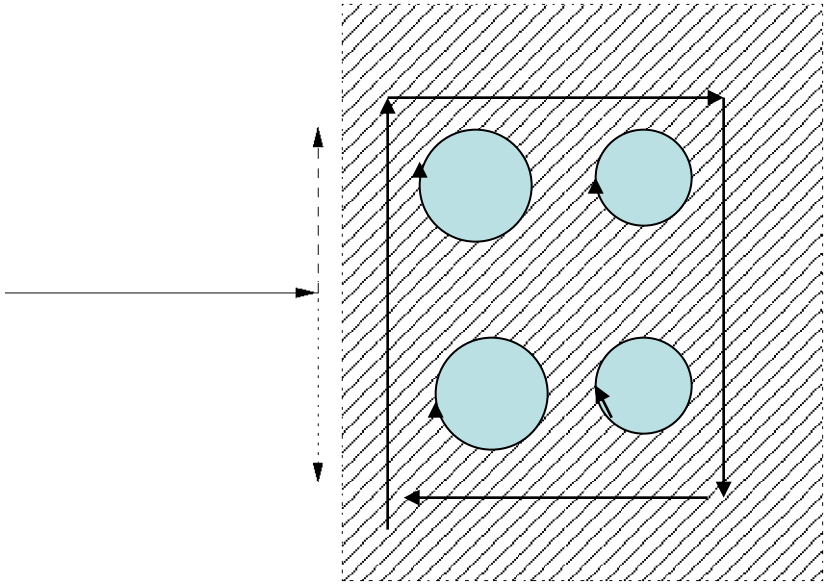
Yin-Yang Reflection

- Multiple scattering used.
- For a line source at 1.5 a in front of an array of YIG rods. a=8mm, 5GHz.
- (a), (b) are for E, (b) is just the amplitude
- (c) is the Poynting vector
- (d) is at a different frequency.



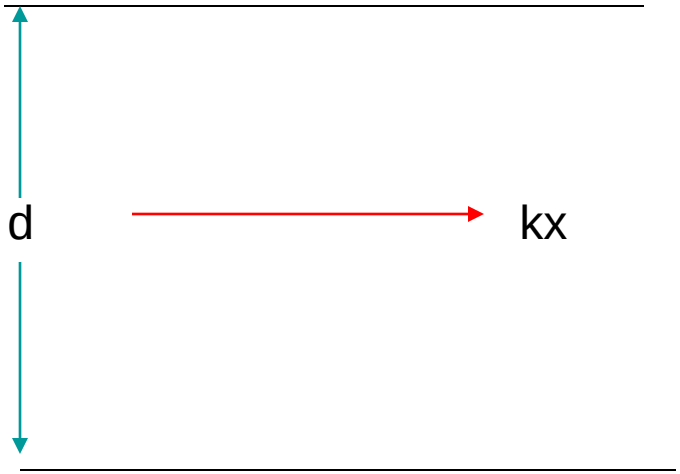
Probing states of macroscopic circulations

- **The eigenstates inside the MPC has contributions from the sum of all the small "eddies" .**



Diffraction limit of waveguides:Plasmonics

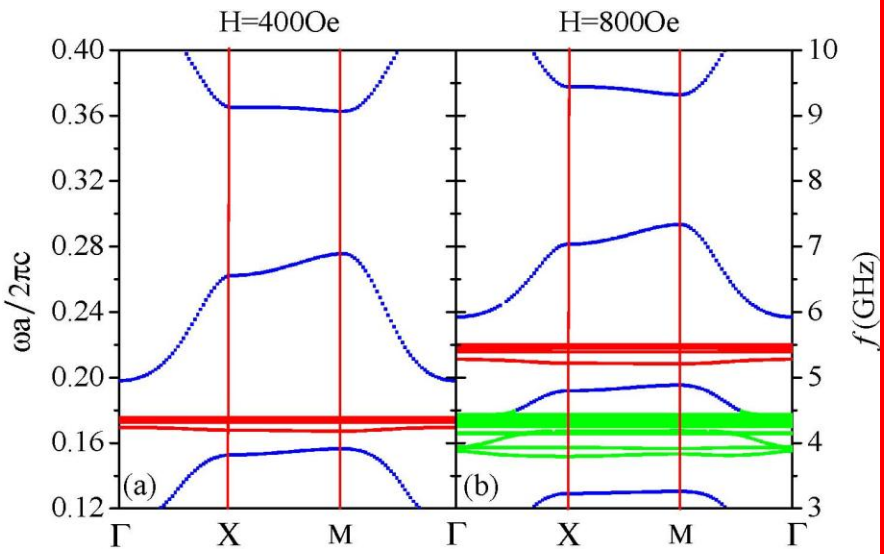
- $k_x^2 = \omega^2/c^2 - \pi^2/d^2$.
- k_x is imaginary if $d < \pi c/\omega$
- EM waves carried by surface plasmonics is suggested as a way to bypass this



Magnetic surface plasmon bands

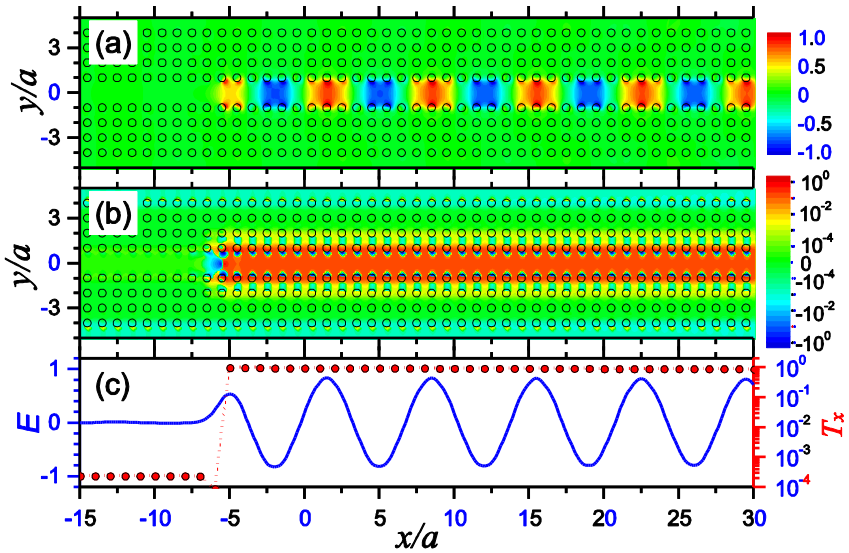
[PRB 78, 155101 (2008)]

- for an array of ferrite cylinders (Ni-Zn) (r=3.3mm, a=12mm)
- μ of the cylinder (not the average μ) = -1
- Physically, this is like a state of coupled surface plasmon.
- Band is flat!
- Similar to the surface plasmon band first seen by Maraduddin et al.



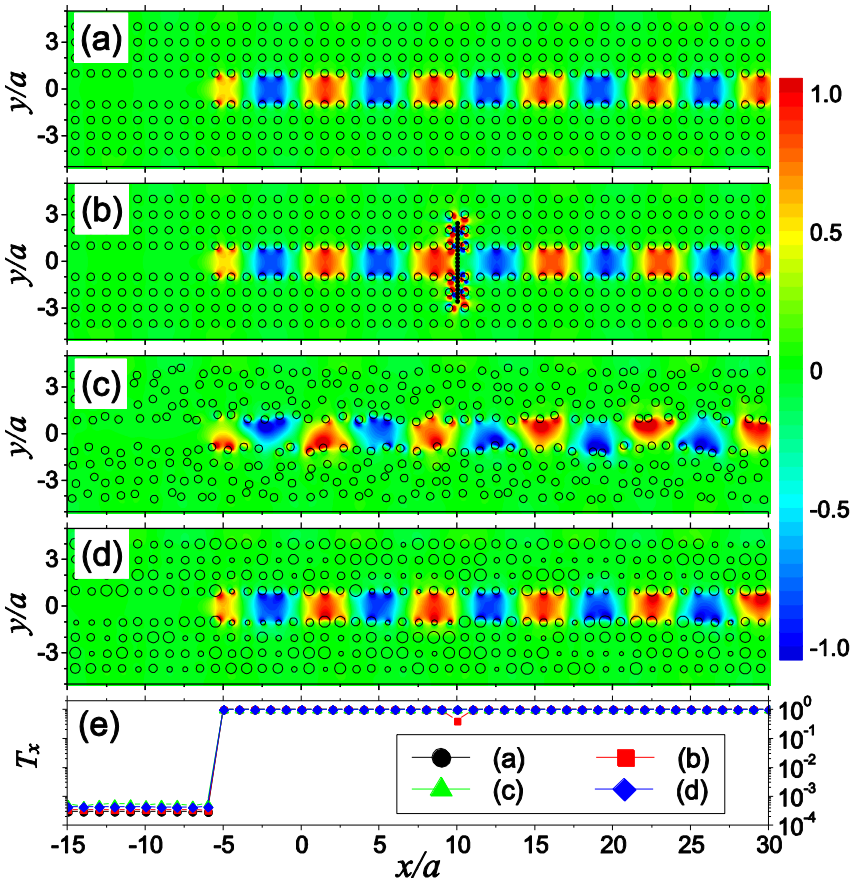
One-way waveguide

- Magnetizations on the two sides are opposite.
- (a) electric field, (b) Poynting vector.
- Source is at x/a= -5.5
- Wave does not go left!



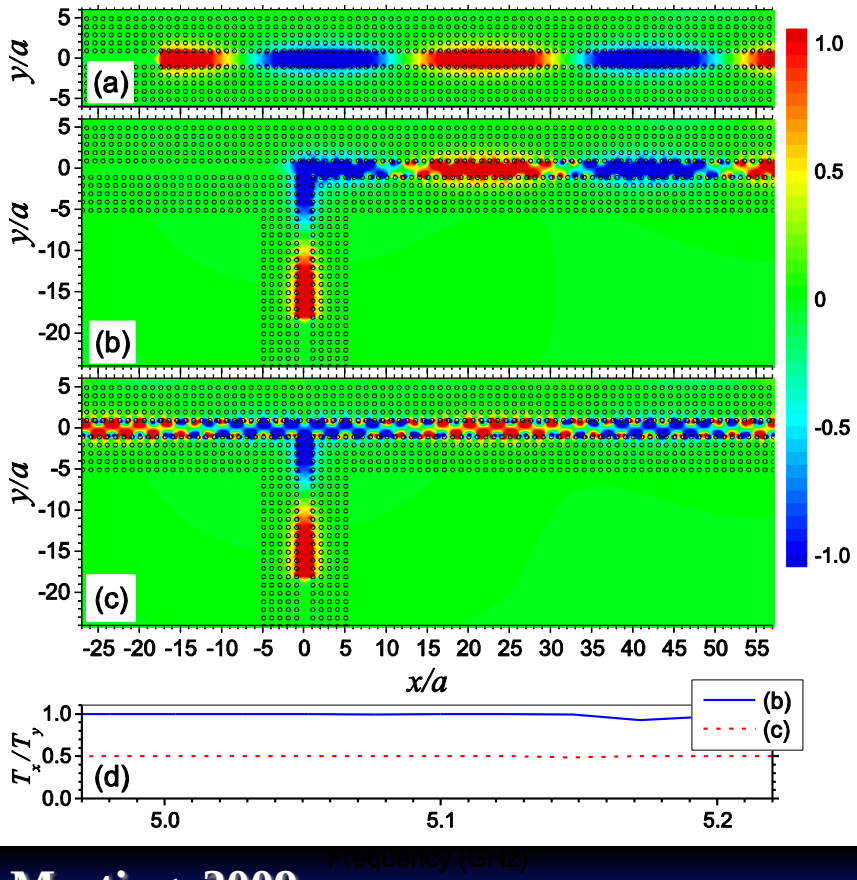
"Superflow" properties

- (a) E field with no defects.
- (b) Close-packed array of cylinders.
- (c) Random position.
- (d) Random size.
- (e) Poynting vector in the channel remains unchanged!



Subwavelength guides, benders and splitters

- Width=wavelength/30
- (b) Top magnetization = that of lower right
- (c) Left magnetization opposite that on the right.
- (d) Transmission efficiency =1.



Magnetic surface plasmon *bands*

Surface Plasmon : $\varepsilon=-1$

Magnetic Surface Plasmon: $\mu=-1$

(Duke group)

Magnetic surface plasmon bands

[PRB 78, 155101 (2008)]

- for an array of ferrite cylinders (Ni-Zn) (r=3.3mm, a=12mm)
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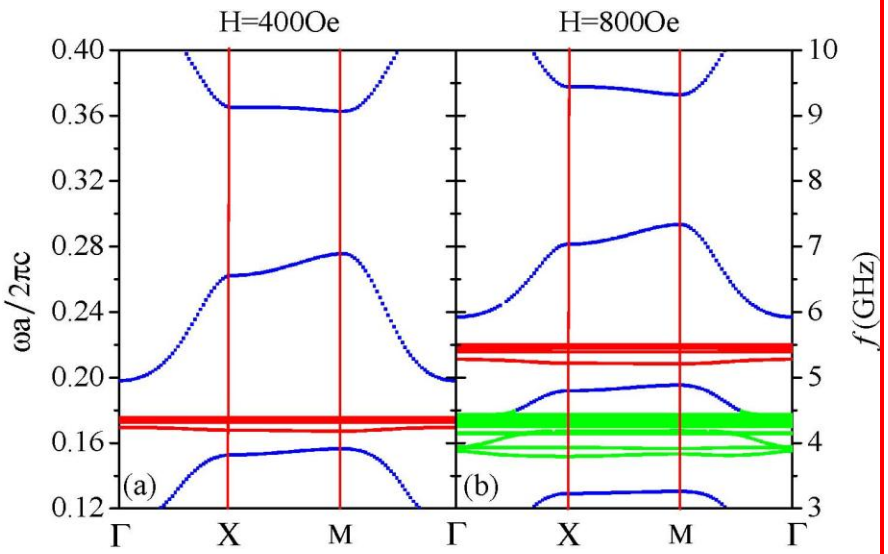
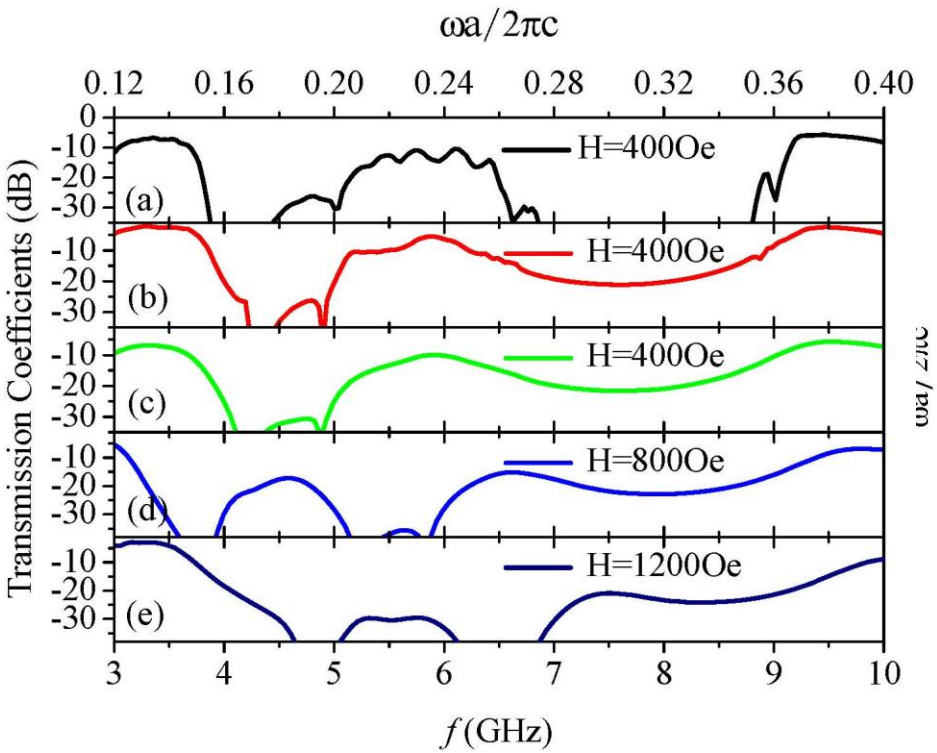
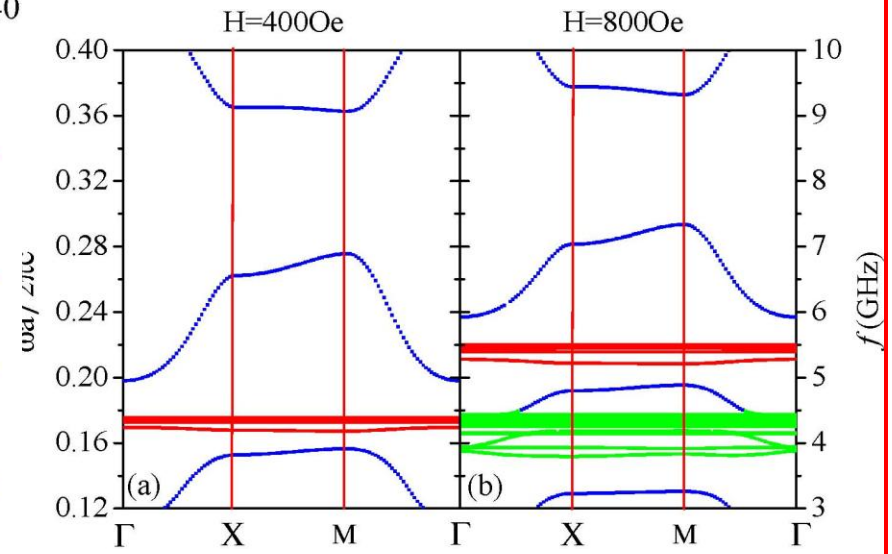


Magnetic surface plasmon bands

[PRB 78, 155101 (2008)]





Resonance bands:

- Photonic behavior is governed entirely by the scattering phase shifts.
- Scattering phase shift of the cylinder $\eta=\pi/2$ in the long wavelength limit at both SP and MSP resonance frequencies.
- Same phase shifts can also be produced by other resonances, for example, a Mie scattering resonance.
- [arXiv: 0808-1554v2 (2008)]

Pseodopotential:

Low loss, indexed match negative refracting material with no "ε<0" metallic components.

Motivated by the CPA calculation of :

[1] Y. Wu, J. S. Li, Z. Q. Zhang, and C. T. Chan, Phys. Rev. B 74, 085111 (2006);

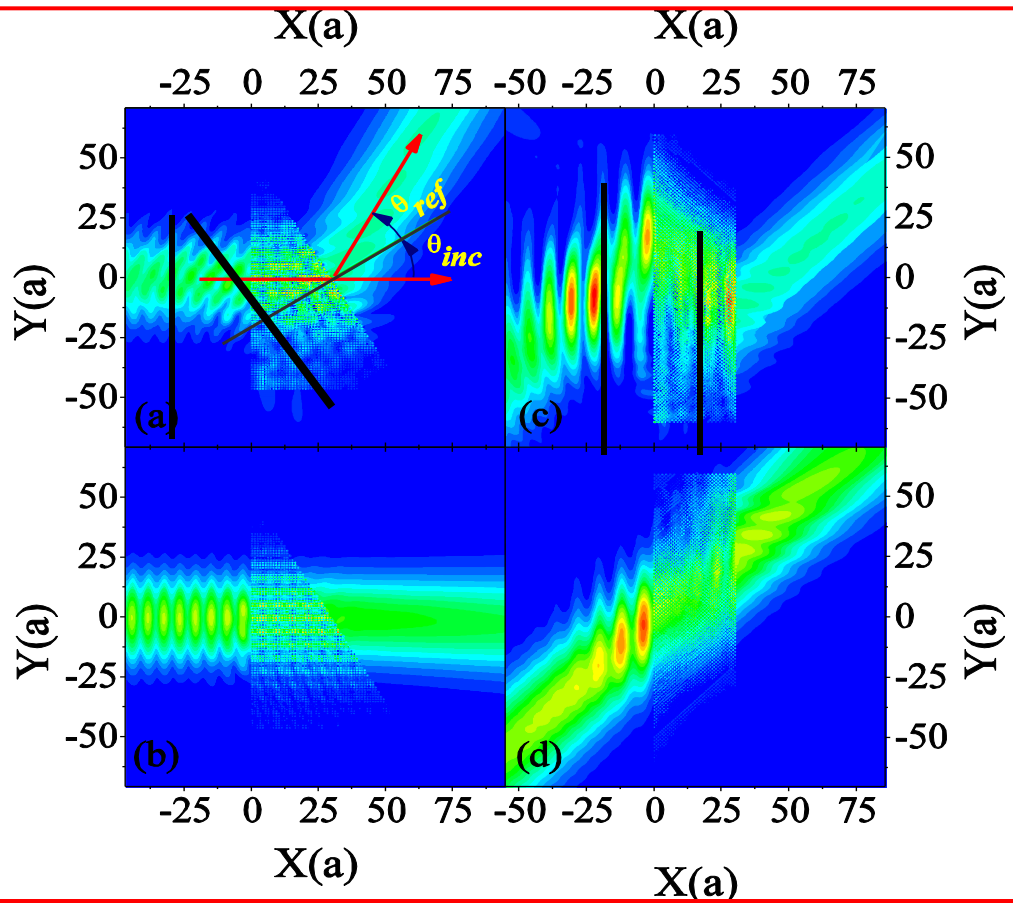
[2] X. H. Hu, C. T. Chan, J. Zi, M. Li and K. M. Ho, PRL 96, 223901 (2006).

Previous system: negative μ and ε for negative refraction

- Metallic wires for negative ε;
- Split rings for μ.

Wedge and of ferrite rods. Index matched, No wires, less damping.

- PRL 101, 157401 (2008).
- Index and impedance matched, no reflection; $\varepsilon=\mu=-1$.
- (a), (c); H_0=500 Oe;
- (b), (d), H_0=475 Oe.



Physics

- Negative ε from engineering of the scattering phase shift. Just like in the pseudo-potential idea in electronic band structure. Negative μ from the spin wave resonance.

Nanowire structures: Systematic approach develpoed

Example: a straight wire

- Studied by Van Vleck,…
- In the thin wire limit, the resonance wavelength is given by
- $\lambda_r = 2L/n$ where n is an integer, L is the length of the wire.

Another example: split rings

- Topologically equivalent to a straight wire;
- Can be analytically solved in the quasi-static limit.

Giant "Faraday effect" at optical frequencies through helixes

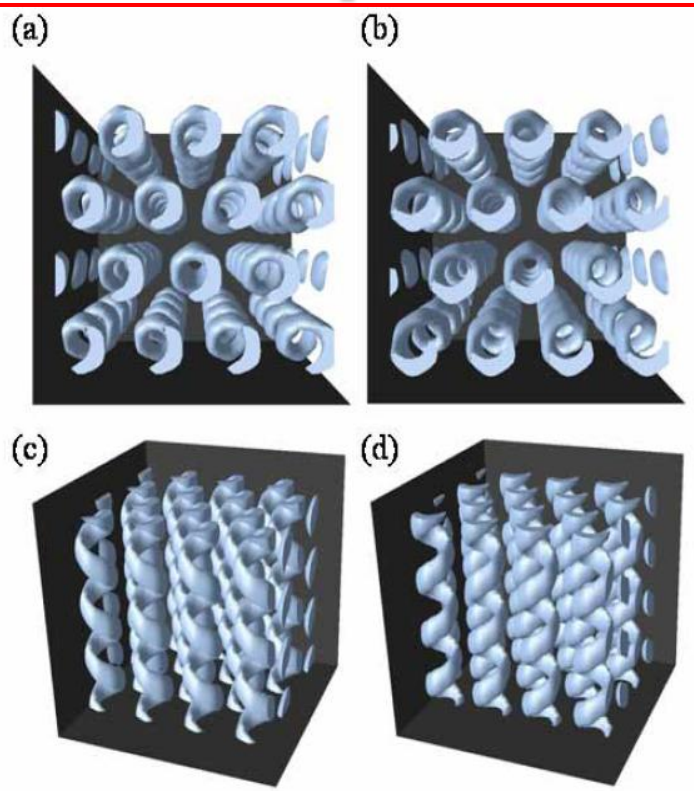


Fig. 2. Intensity contour surfaces of (a) and (c) left handed and (b) and (d) right handed spirals using the 6+1 beams interference of Eq. (3).

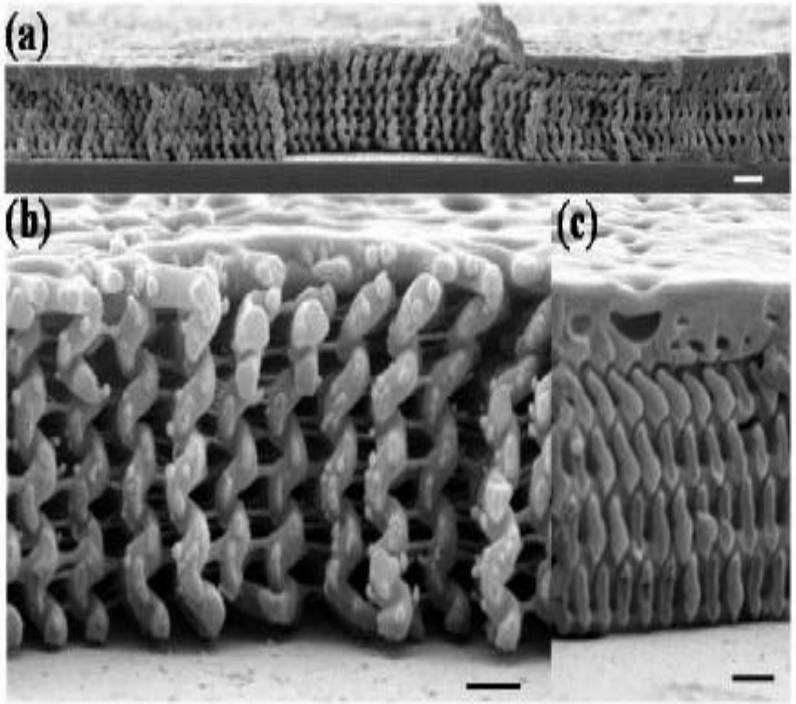


Fig.3. SEM images of spirals: (a) overall (b) close-up views. (c) Structure with out off phase interference. Scale bar is: (a) 2 μm, (b) 1 μm, and (c) 1 μm..

Physics of wire structures

Systematic approach in the quasi-static limit

How to generalize Kirchoff law to finite frequencies?

- **For D. C. we have the potential at each junction .**
- **For A.C. introduce localized electric fields *e* at ends and junctions.**
- **Motivation: currents are now spatially varying.**
- **$\partial \rho / \partial t = -r ¢ j$.**
- **The spatial derivative of the current does NOT conserve at a junction, charges and localized fields are generated.**

Split ring resonance frequency can be calculated analytically

- $I(\phi)=\sum_m \exp(im\phi)\, I_m$
- Impedence: $X_m=i\omega\,(L_m-m^2/\omega^2\, C_m)\ +r$.
- Circuit equation: $X_m\, I_m\ =\ E_m + e$
- Boundary condition: $I(0)=\sum_m I_m=0$.
- $e =-\sum_m E_m /X_m /[\ \sum_m 1 / X_m\ ]$

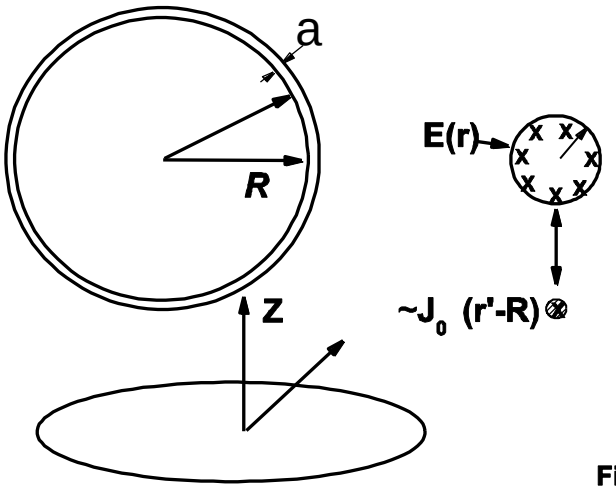


Fig. 1

Split ring resonance frequency can be calculated analytically

- $I(\phi)=\sum_m \exp(im\phi)\, I_m$
- Impedence: $X_m=i\omega\,(L_m-m^2/\omega^2\, C_m)\ +r$.
- $e=-\sum_m E_m/X_m/[\sum_m 1/X_m]$
- For resonance, set $E_m=0$
- $\sum_m 1/X_m\ (\omega_r)=0$

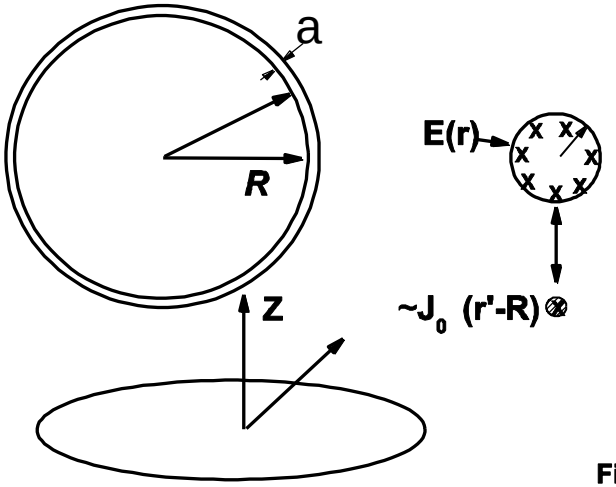


Fig. 1

Many interesting results

- Can design sub-sub-wavelength resonantors so that the resonant wavelength is more than a thousand times its size.
- For an applied field of 1 V/m, at resonance, the field at the end can be near the dielectric breakdown field of 3x 10^6 V/m.
- Can design structures with faraday rotation that is 1000 times bigger than TGG.

Circuit equation can be exactly solved for the resonance

[JAP 104, 034305 (2008)]

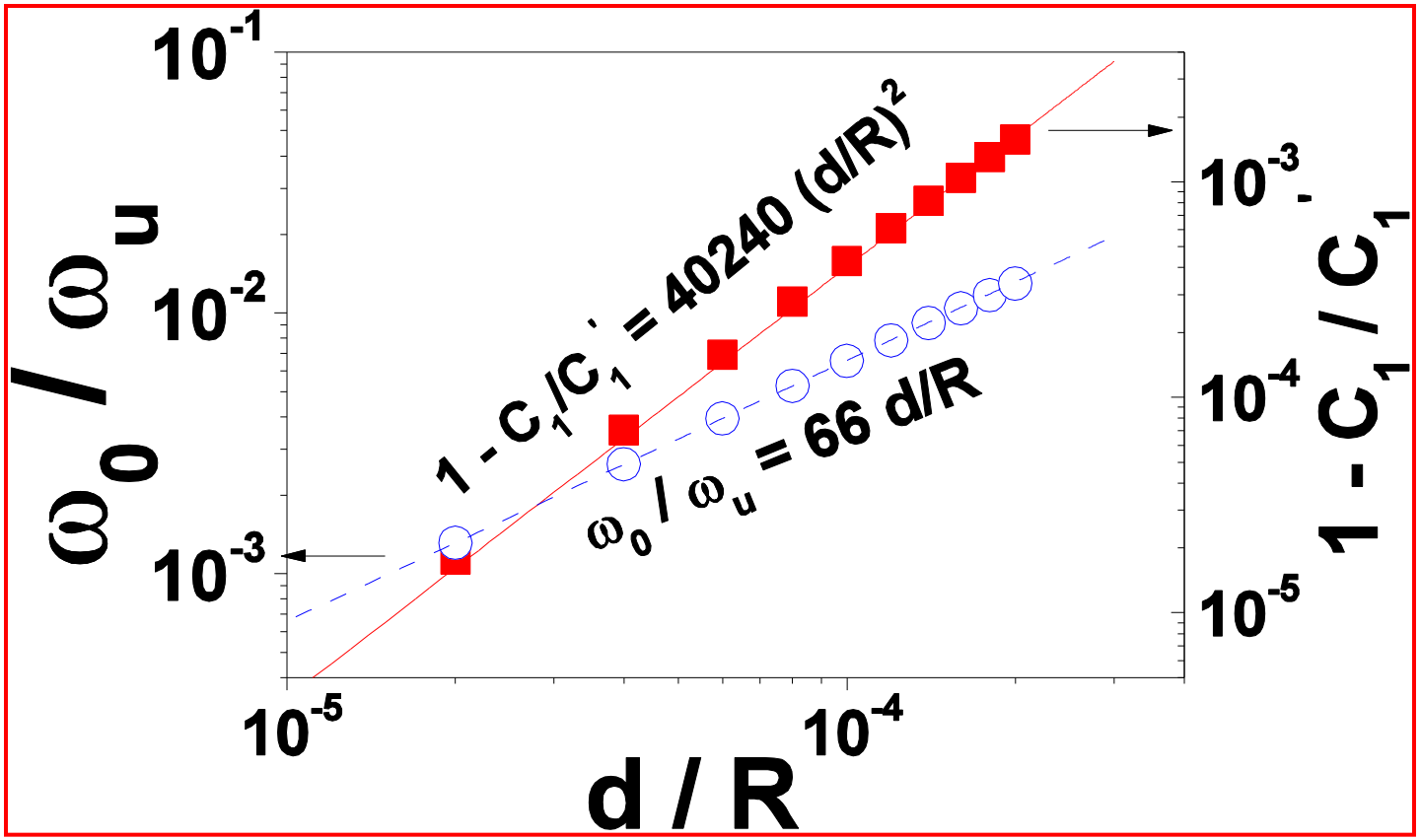
- **Eigenvalue equation for the resonance frequency:**

- $1 + \sum_{m=1}^{1} 2(L_0\omega^2 - ir_c)/(L_m\omega^2 - m^2/C_m - ir_c) = 0.$
- r_c **is the conductor resistance.**

For narrow wires, all L, C are the same; resonance wavelength the same as a straight wire

- **eigenvalue equation becomes**
  $1 + \sum_{m=1}^{1} 2\omega^{2}/(\omega^{2} - m^{2}\omega_{u}^{2}) = 0.$
  $$k\pi\cot(k\pi) = 1 + \sum_{m=1}^{\infty} 2k^{2}/(k^{2} - m^{2})$$
- **$\cot(\omega\pi/\omega_{u}) = 0$**
- **spectrum for the magnetic modes is given by $(n+1/2)\omega_{u}$ where $\omega_{u} = 1/(L_{0}C_{1})^{0.5}$**

Resonance frequency [ω_u=c/R] can be very small!



Giant Faraday rotation with metallic helixes

Thank you