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Morphology Dependence on the Magnetic Performance of Nanomaterials

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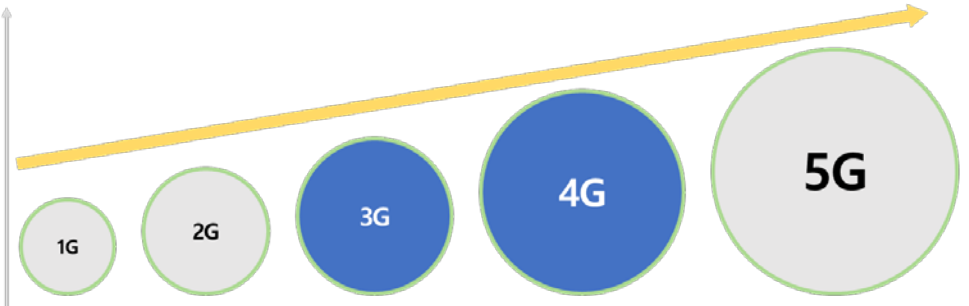
Introduction

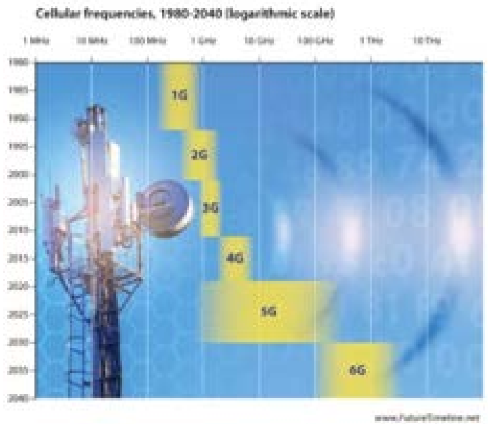
Applications of Magnetic Nanomaterials in high frequency range

Fueling the 5G Expansion in the Next Decade



Maximum transmission speed	14.4 Kbps	144 Kbps	14 Mbps	75 Mbps	20 Gbps
Main application	Voice calling	Text message	Video calling	Data usage/Streaming	IOT/VR-AR/Hologram
Commercialized in	1984	2000	2006	2011	2019

- 5G networks promise better connectivity, higher speeds, and less latency, or the time it takes for a signal to travel from a wireless device to a data center and back.
- Internet of Things (IoT) solutions will connect more than 50 billion devices by 2030. While 5G is still rolling out at neck-breaking speed, the resulting evolution in communications will bring the world to a faster, smarter future.



- Beyond 5G, 6G technology is rising.
- Samsung planning on commercializing 6G technology in 2030.

Snoek's law:

$$(\mu_s - 1) f_{res} = \frac{2}{\beta} \gamma 4\pi M_0$$

Generalized Snoek's Law

- Magnetic materials with high frequency permeability:

$$\mu(f) = \mu'(f) - i\,\mu''(f)$$

→ where f = frequency

- The high frequency permeability of a material can be evaluated based on the frequency of its ferromagnetic resonance (FMR), f_{res}, and the static permeability, μ_s.

→ where f_{res} = frequency, above which the material is non-magnetic
μ_s = estimate of the permeability at lower frequencies

- For the majority of materials, the product of these values is limited according to Snoek's law:

$$(\mu_s - 1) f_{res} = \frac{2}{3}\gamma 4\pi M_0 \qquad (1)$$

→ where $4\pi M_0$ = saturation magnetization
γ = 3GHz/kOe is the gyromagnetic ratio

Generalized Snoek's Law

- However, equation (1) limits the achievable values of the high-frequency permeability. The materials, in which Snoek's limit is exceeded, is of the great interest.

- Equation (1) is rewritten for these materials:

$$(\mu_s - 1) \cdot f_{res}^2 \leq (\gamma 4\pi M_0)^2$$

- The most important examples of such materials are thin ferromagnetic films, composites with flake-shaped magnetic inclusions, hexagonal ferrites, and one-dimensional nanomagnetic materials, which will be introduced in the next section.

chapter 02

SOA of Magnetic Materials with High Permeability Working at High Frequency Range

Shape controlling

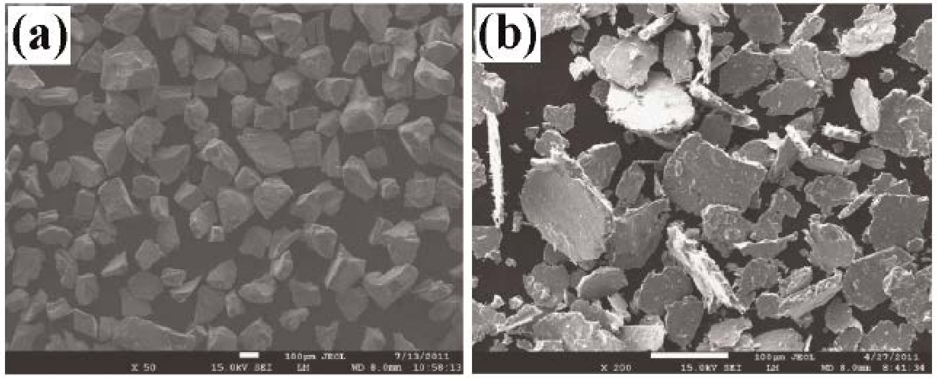


Figure 1.
SEM pictures: (a) preliminarily pulverized particles and (b) particles with flaky shapes prepared by 30 hours of ball milling.

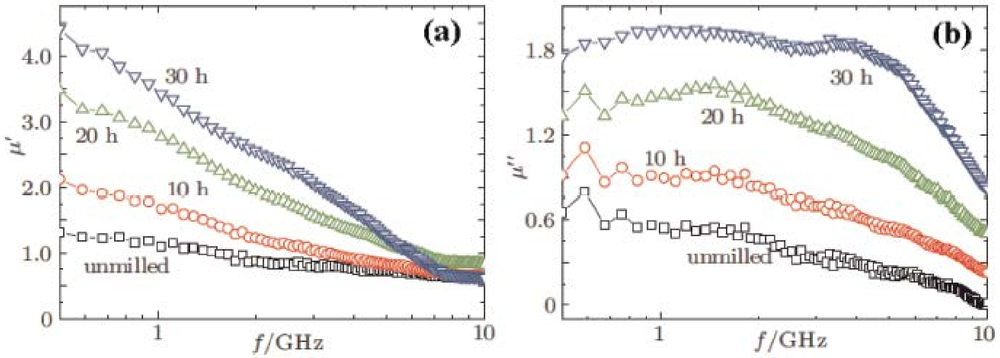


Figure 2.
Dependence of high-frequency permeability on particle shapes (copyright, 2013, IOP).

- Enhanced permeability of Fe-Si-Al alloys above 1 GHz via shape controlling.
- Flaky particles have much larger values in both real and imaginary parts of permeability compared to the irregularly shaped particles.
- The μ′ value of flakes after being milled for 30 hours is found to be 4.4 at 0.5 GHz. However, it is only 1.3 for the irregular shaped particle.
- Within 0.5–7 GHz, the μ′ values of flakes after being milled for 30 hours are evidently larger than those of particles with irregular shapes.

Shape controlling

- Application of Snoek's law (shape factors included):

$$(\mu_s - 1) f_r^2 = \left(\frac{\gamma}{2\pi}\right)^2 \times 4\pi \mathrm{M}_s \times (H_k + 4\pi M_s D_z)$$

where D_z = demagnetization factor for the normal direction of the particle plane.

- D_z ~ 4π/3 for a sphere and 4π for a flake.
- Enhanced permeability value can be observed by increasing D_z from (4π/3) to (4π) by controlling the particle shapes.

Particle size distribution

- Fe-Cu-Nb-Si-B alloy particles (a.k.a. “FINEMET” alloy) are prepared for flakes with different sizes: large flakes and small flakes.

	Initial Permeability (μ'_s)	Initial imaginary part permeability (μ''_s)
Large flakes	4.6	1.3
Small flakes	3.9	0.9

- However, small flakes show higher permeability value at higher frequency range.

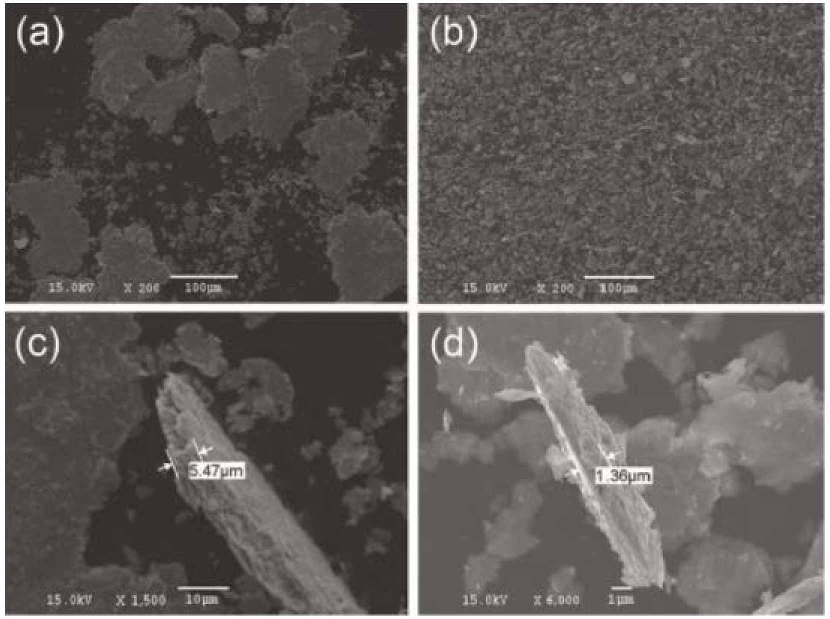


Figure 5.
SEM images of two categories of flakes: (a) large flakes; (b) small flakes; (c) typical thickness of large flakes; (d) typical thickness of small flakes (copyright, 2015, AIP).

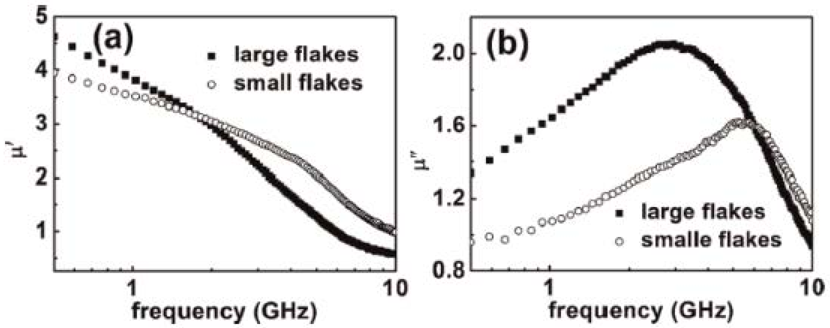


Figure 6.
High-frequency permeability of composites contained different sizes of Fe-Cu-Nb-Si-B flakes. (a) μ' ~ f spectra and (b) μ ~ f spectra (copyright, 2015, AIP).

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Particle size distribution

- Application of Snoek's law (shape factors included):

$$\mu_s = 1 + \frac{4\pi M_s}{(H_k + 4\pi M_s N_h)}$$

$$f_r = \frac{\gamma}{2\pi}\sqrt{H_k^2 + 4\pi M_s H_k (N_\perp + N_h) + (4\pi M_s)^2 N_\perp N_h}$$

$$N_\perp = \frac{\alpha_r^2}{\alpha_r^2 - 1} \times \left(1 - \sqrt{\frac{1}{\alpha_r^2 - 1}} \times ars\sin\frac{\sqrt{\alpha_r^2 - 1}}{\alpha_r}\right)$$

$$N_h = \frac{1 - N_\perp}{2}$$

where α_r = width/thickness ratio of a flake
$N_\perp$ = demagnetization factor along the direction of thickness
N_h = demagnetization factor along the direction of width

- Reflection loss (RL, in dB):

$$Z_{in} = Z_0\sqrt{\frac{\mu}{\varepsilon}}\tanh\left(j\frac{2\pi f d}{c}\sqrt{\mu\varepsilon}\right)$$

$$R.L. = 20\log\left|\frac{Z_{in} - Z_0}{Z_{in} + Z_0}\right|$$

where d = thickness of composite layer
c = velocity of light
Z_0 = impedance of free space
Z_{in} = characteristic impedance at the free space/absorber interface

Particle size distribution

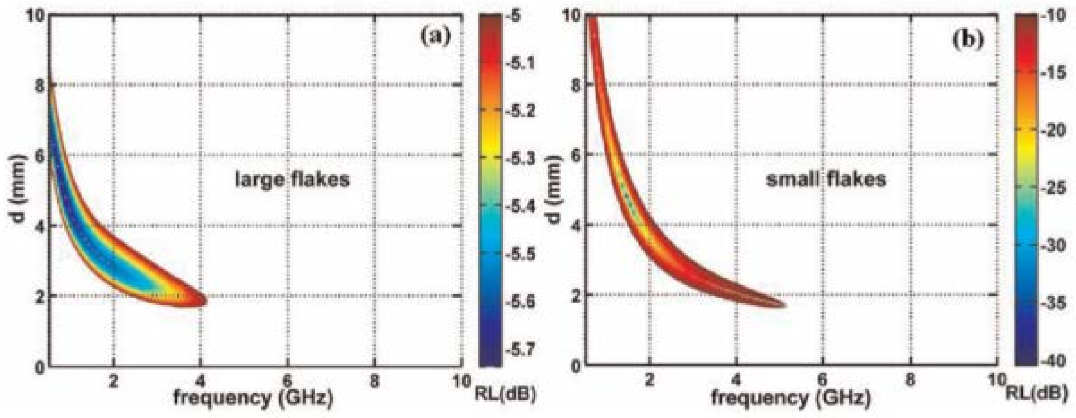

Figure 7.
Contour maps showing the absorbing properties of single layer composites with different flakes: (a) large flakes and (b) small flakes (copyright, 2015, AIP).

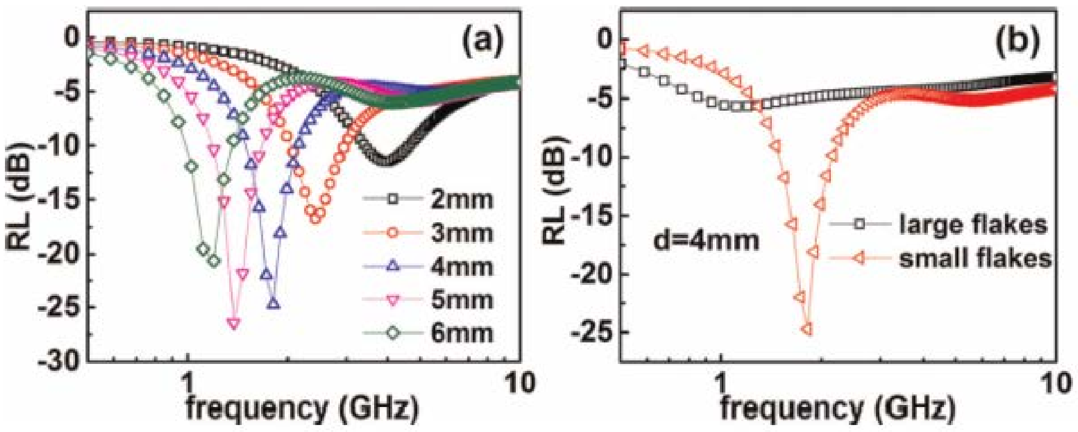

Figure 8.
(a) Composites filled with smaller flakes and with different thickness and (b) composite filled with different flakes but with same thickness (4 mm) (copyright, 2015, AIP).

- Composites containing smaller flakes have better absorbing performances in terms of RL as well as reduced absorber thickness.

chapter 03

Conclusion

Conclusion

- 5G technology is expected to deliver speeds up to 100 times faster than typical 4G technology.
- Also, technology beyond 5G will certainly change the way we spend our lives, our communications will be faster than we can imagine and our connections will be stronger.
- Nanomagnetic material with tailored morphology working at high frequencies will shape our way to high frequency needed applications.
- The high frequency permeability of a material can be evaluated based on the frequency of its ferromagnetic resonance (FMR), f_{res}, and the static permeability, μ_s, where the product is limited by the Snoek's law.
- Application of Snoek's law with shape factors included will guide us to preparing morphology tailored ferromagnetic materials with high frequency permeability.

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Thank You