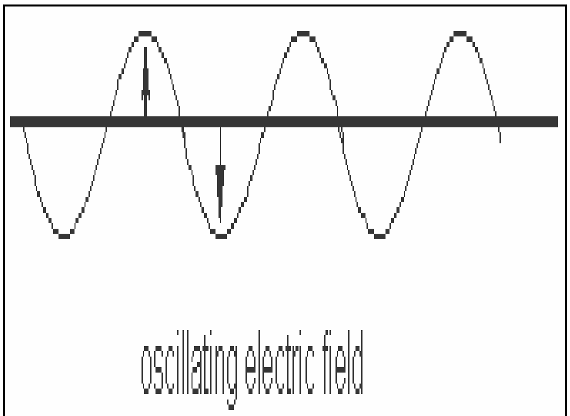
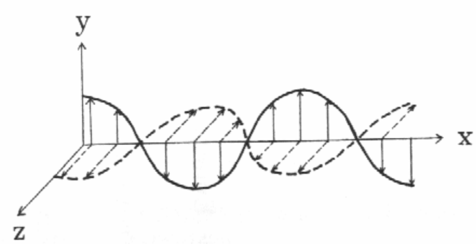
Electromagnetic applications

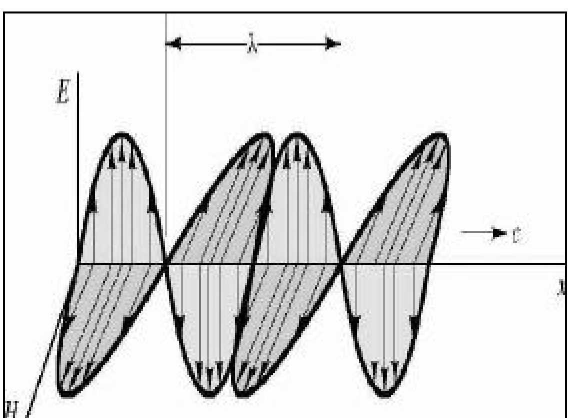
Topic 6

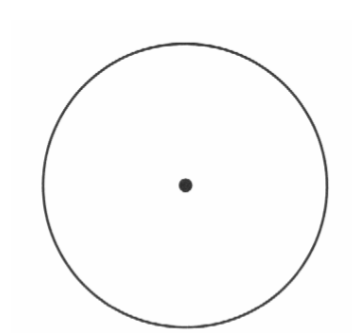
Reading assignment

- Chung, Composite Materials, Ch. 5.
- No. 81 under "Publications – carbon" in website http://www.wings.buffalo.edu/academic/department/eng/mae/cmrl





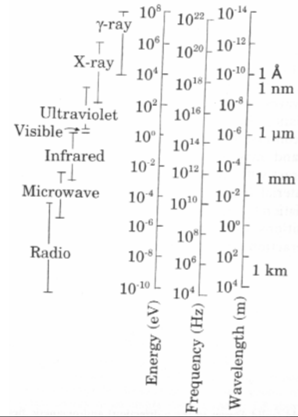


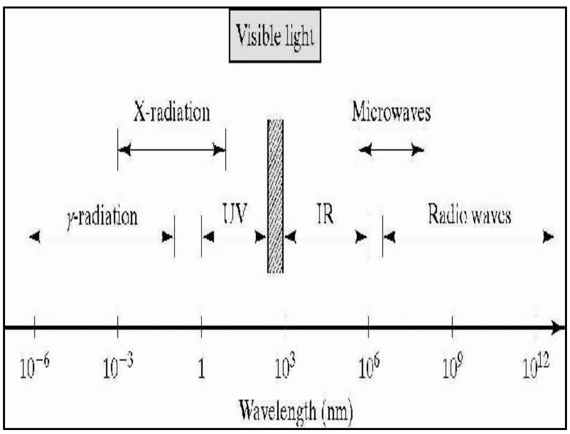


Coaxial cable

Electromagnetic radiation is in the form of waves called photons.
The important characteristics of the photons—their energy *E*, wavelength ?, and frequency ?—are related by the equation

$$E = h\nu = \frac{hc}{\lambda}$$





Electromagnetic applications

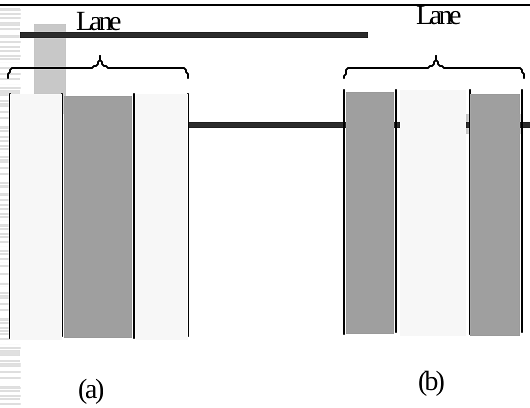
- Electromagnetic interference (EMI) shielding
- Low observability (Stealth)
- Electromagnetic transparency (radomes)

Electromagnetic shielding applications

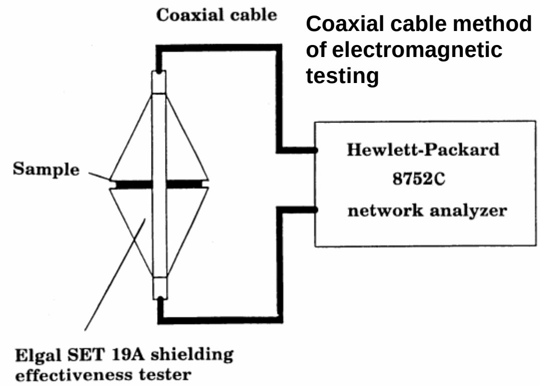
- **Electronic enclosures (e.g., computers, pacemaker leads, rooms, aircraft, etc.)**
- **Radiation source enclosures (e.g., telephone receivers)**
- **Cell-phone proof buildings**
- **Deterring electromagnetic form of spying**

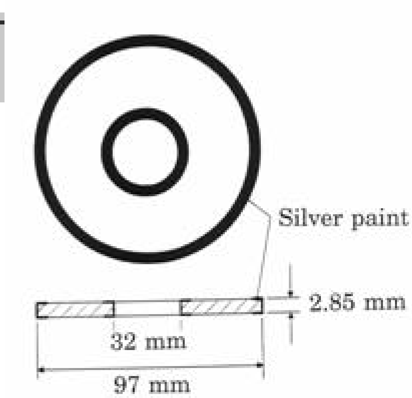
Electromagnetic applications

- **Electronic pollution**
- **Telecommunication**
- **Microwave electronics**
- **Microwave processing**
- **Lateral guidance**



Coaxial cable method of electromagnetic testing





Reflectivity R

Fraction of energy of the electromagnetic radiation that is reflected

Absorptivity A

Fraction of the energy of the electromagnetic radiation that is absorbed

Transmissivity T

Fraction of the energy of the electromagnetic radiation that is transmitted

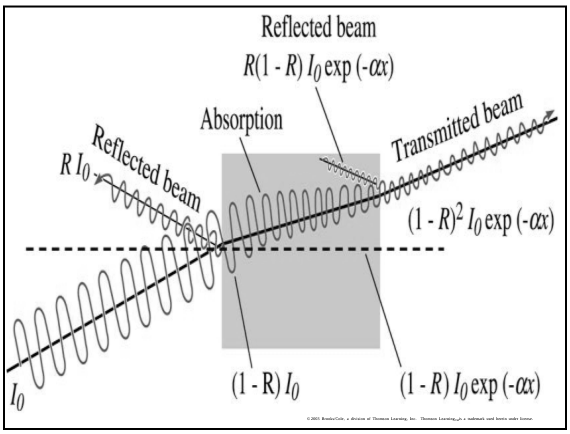
R + A + T = 1

The transmitted portion is the portion that has not been absorbed or reflected.

The attenuation in decibels (dB) is defined as

$$\text{Attenuation (dB)} = 20 \log_{10} (E_i/E),$$

where E_i is the incident field and E is the transmitted or reflected field. Note that $E_i > E$.



Mechanisms of interaction of electromagnetic radiation with materials

- **Reflection**
- **Absorption**
- **Multiple reflection**

Reflection

Mainly due to interaction of electromagnetic radiation with the electrons in the solid

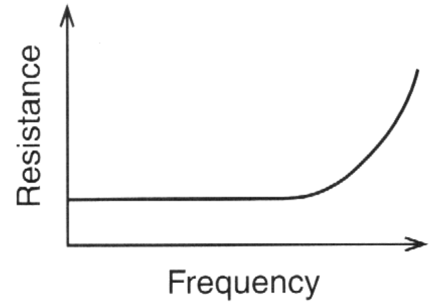
Skin Effect

Phenomenon in which high frequency electromagnetic radiation interacts with only the near surface region of an electrical conductor

Skin depth (δ)

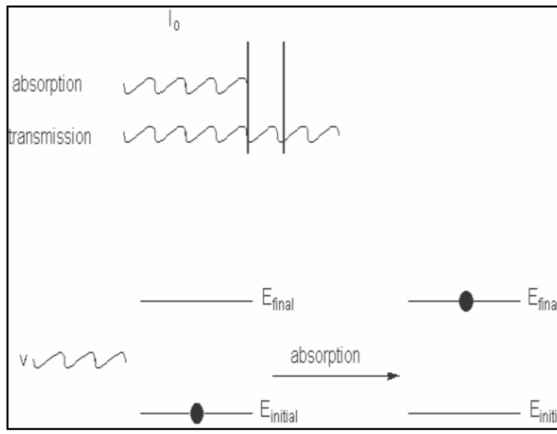
$$d = \frac{1}{\sqrt{pfms}},$$

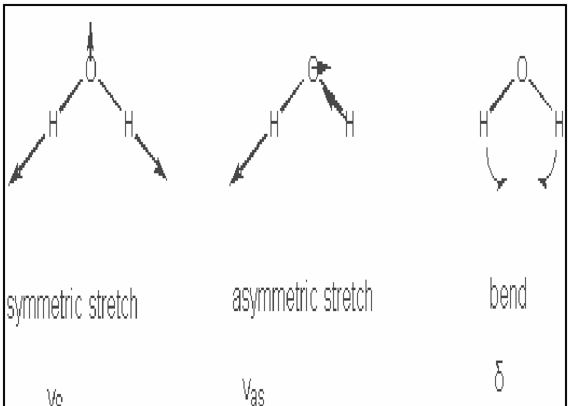
where f = frequency,
μ = magnetic permeability = $\mu_0\mu_r$,
μ_r = relative magnetic permeability,
$\mu_0 = 4\pi \times 10^{-7}$ H/m, and
σ = electrical conductivity in $\Omega^{-1}m^{-1}$.

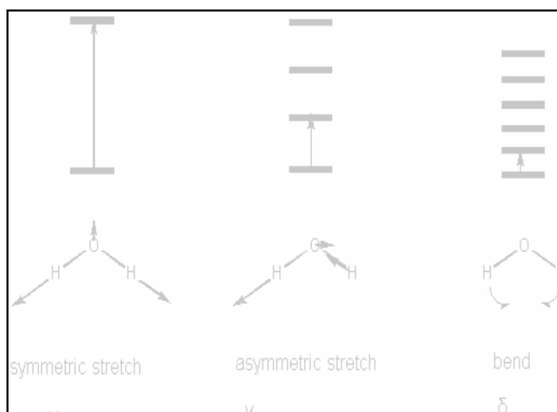


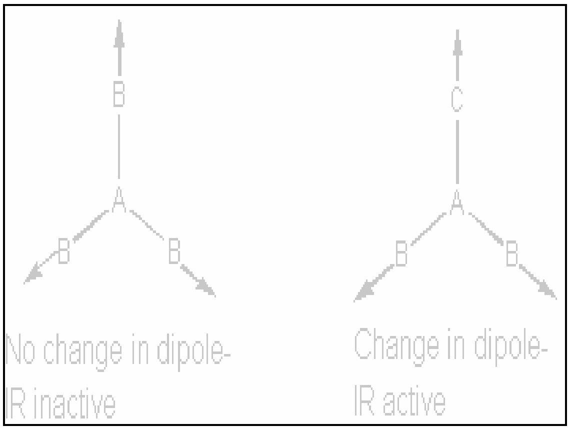
Absorption

Due to interaction of electromagnetic radiation with the electric/magnetic dipoles, electrons and phonons in the solid









Material attributes that help shielding

- Electrical conductivity
- Magnetization
- Electrical polarization
- Small unit size
- Large surface area

Table 5.1. Electrical conductivity relative to copper (σ_r) and relative magnetic permeability (μ_r) of selected materials.

Material	s_r	m_r	$s_r m_r$	s_r/m_r
Silver	1.05	1	1.05	1.05
Copper	1	1	1	1
Gold	0.7	1	0.7	0.7
Aluminum	0.61	1	0.61	0.61
Brass	0.26	1	0.26	0.26
Bronze	0.18	1	0.18	0.18
Tin	0.15	1	0.15	0.15
Lead	0.08	1	0.08	0.08
Nickel	0.2	100	20	2×10^{-3}
Stainless steel (430)	0.02	500	10	4×10^{-5}
Mumetal (at 1 kHz)	0.03	20,000	600	1.5×10^{-6}
Superpermalloy (at 1 kHz)	0.03	100,000	3,000	3×10^{-7}

Electromagnetic shielding materials

- Nanofiber is more effective than fiber, due to small diameter and the skin effect.
- Thermoplastic matrix: nanofiber (19 vol.%) gives shielding 74 dB at 1 GHz, whereas fiber (20 vol.%, 3000 microns long) gives 46 dB.
- Cement matrix: nanofiber (0.5 vol.%) gives 26 dB, whereas fiber (0.8 vol.%) gives 15 dB.

Nanofiber inferior to the following fillers for shielding

- **Carbon fiber (400 microns long)**
- **Nickel fibers (2 and 20 microns diameter)**
- **Aluminum flakes**

Nickel coated carbon nanofiber

- **Diameter: 0.4 micron**
- **Carbon core diameter: 0.1 micron**
- **Nickel by electroplating**
- **87 dB at 7 vol.% (thermoplastic matrix)**
- **Much better than uncoated carbon nanofiber and nickel fibers.**

Table 1. Electromagnetic interference shielding effectiveness at 1-2 GHz of PES-matrix composites with various fillers

Filler	Vol. %	EMI shielding effectiveness (dB)
Al flakes (15 x 15 x 0.5 µm)	20	26
Steel fibers (1.6 µm dia. x 30 ~ 56 µm)	20	42
Carbon fibers (10 µm dia. x 400 µm)	20	19
Ni particles (1~5 µm dia.)	9.4	23
Ni fibers (20 µm dia. x 1 mm)	19	5
Ni fibers (2 µm dia. x 2 mm)	7	58
Carbon filaments (0.1 µm dia. x > 100 µm)	7	32
Ni filaments (0.4 µm dia. x > 100 µm)	7	87

Cement pastes (with 1 vol. % conductive admixture) for EMI shielding at 1 GHz

- Steel fiber (8 microns) 58 dB
- Carbon fiber (15 microns) 15 dB
- Carbon nanofiber (0.1 micron) 35 dB
- Graphite powder (0.7 micron) 22 dB
- Coke powder (less than 75 microns) 47 dB

Cement pastes (with 1 vol.% conductive admixture)

- Steel fiber (8 microns) 40 ohm.cm
- Carbon fiber (15 microns) 830 ohm.cm
- Carbon nanofiber (0.1 micron) 12,000 ohm.cm
- Graphite powder (0.7 micron) 160,000 ohm.cm
- Coke powder (less than 75 microns) 38,000 ohm.cm

EMI gaskets

- Shielding effectiveness
- Resiliency

EMI gasket materials

- Metal coated elastomers
- Elastomers filled with conductive particles
- Flexible graphite

Reasons for outstanding performance of flexible graphite (130 dB at 1 GHz)

- High specific surface area
- Resilience
- Conductive

Table 1 EMI Shielding effectiveness and DC electrical resistivity of various EMI Gasket materials

Material	Shielding effectiveness at 0.3 MHz – 1.5 GHz (dB)	Thickness (mm, ± 0.02)	Resistivity (Ωm)
Flexible graphite A	125.4 ± 5.1	3.10	(7.5 ± 0.2) x 10^{-6}
Flexible graphite A	125.4 ± 6.5	1.60	(7.5 ± 0.8) x 10^{-6}
Flexible graphite A	122.6 ± 8.9	0.79	(7.10 ± 0.03) x 10^{-6}
Flexible graphite B	120.6 ± 7.0	1.14	(1.6 ± 0.3) x 10^{-5}
Silicone/Ag-Cu	120.4 ± 9.5	3.00	(7.5 ± 1.4) x 10^{-4}
Silicone/Ag-glass	116.0 ± 12.6	3.00	(9.8 ± 0.7) x 10^{-4}
Silicone/Ni-C	93.7 ± 14.1	2.74	(1.17 ± 0.13) x 10^{-3}
Silicone/carbon black	14.92 ± 0.56	1.59	(4.46 ± 0.15) x 10^{-3}
Silicone/oriented wire	0.31 ± 0.13	1.59	(1.07 ± 0.17) x 10^{3}

Carbon materials for EMI shielding

- **Flexible graphite (130 dB at 1 GHz)**
- **Nickel coated carbon nanofiber (7 vol. %) polymer-matrix composite (87 dB at 1 GHz)**
- **Coke particle (1 vol. %) cement-matrix composite (47 dB at 1 GHz)**

Table 1 Attenuation upon transmission, attenuation upon reflection and transverse electrical resistivity of carbon fiber epoxy-matrix composites at 1.0 – 1.5 GHz.

Fiber type	Attenuation upon transmission (dB)	Attenuation upon reflection (dB)	Resistivity (Ω.mm)
As-received	29.6 ± 0.9	1.3 ± 0.2	20.7 ± 2.4
Epoxy coated	23.8 ± 0.8	1.7 ± 0.2	70.9 ± 3.8

Table 2 Tensile properties of carbon fiber epoxy-matrix composites. Standard deviations are shown in parentheses

Fiber type	Strength (MPa)	Modulus (GPa)	Elongation at break (%)
As-received	718 (11)	85.5 (3.8)	0.84 (0.03)
Epoxy coated	626 (21)	73.5 (4.4)	0.85 (0.03)

Table 1 Attenuation under transmission and under reflection of carbon fiber composites.

Fiber type	Attenuation upon transmission (dB)	Attenuation upon reflection (dB)
As-received	29.6 ± 0.9	1.3 ± 0.2
Activated	38.8 ± 0.8	1.2 ± 0.2

Table 2 Tensile properties of carbon fibers before and after activation. Standard deviations are shown in parentheses.

Fiber type	Strength (MPa)	Modulus (GPa)
As-received[a]	665 (87)	126 (7)
Activated[b]	727 (151)	138 (15)

[a] Six specimens tested
[b] Eight specimens tested

Table 1 EMI shielding effectiveness (attenuation upon transmission), attenuation upon reflection and electrical resistivity.

Row No.	Material on Mylar (ratio of ingredients by volume)	Attenuation upon transmission (dB)	Attenuation upon reflection (dB)	Resistivity (Ωcm)
1	None	0.7 ± 0.1	21.6 ± 0.8	10^{18} [a]
2	Base paint	1.3 ± 0.2	16.8 ± 0.9	10^{14}
3	Base paint + mumetal (100 : 2)	3.2 ± 0.3	15.9 ± 0.8	33.0 ± 1.6
4	Base paint + mumetal (100 : 5)	5.3 ± 0.4	8.9 ± 0.6	27.8 ± 0.9
5	Base paint + mumetal (100 : 10)[b]	6.9 ± 0.3	6.4 ± 0.4	25.4 ± 0.8

[a] From DuPont's datasheet for Mylar.
[b] Maximum possible filler content.

Table 1 EMI shielding effectiveness (attenuation upon transmission), attenuation upon reflection and electrical resistivity (cont'd).

Row No.	Material on Mylar (ratio of ingredients by volume)	Attenuation upon transmission (dB)	Attenuation upon reflection (dB)	Resistivity (Ωcm)
6	Base paint + graphite flake (100 : 10)[b]	8.5 ± 0.4	5.6 ± 0.5	22.0 ± 1.0
7	Base paint + graphite flake + mumetal (100 : 10 : 2)	8.8 ± 0.5	5.7 ± 0.5	22.5 ± 0.8

[a] From DuPont's datasheet for Mylar.
[b] Maximum possible filler content.

Table 1 EMI shielding effectiveness (attenuation upon transmission), attenuation upon reflection and electrical resistivity (cont'd).

Row No.	Material on Mylar (ratio of ingredients by volume)	Attenuation upon transmission (dB)	Attenuation upon reflection (dB)	Resistivity (Ωcm)
8	Base paint + nickel powder I (100 : 10)[b]	5.8 ± 0.4	7.7 ± 0.5	23.5 ± 1.2
9	Base paint + nickel powder I + mumetal (100 : 10 : 2)	5.6 ± 0.3	7.9 ± 0.4	25.3 ± 0.9

[a] From DuPont's datasheet for Mylar.
[b] Maximum possible filler content.

Table 1 EMI shielding effectiveness (attenuation upon transmission), attenuation upon reflection and electrical resistivity (cont'd).

Row No.	Material on Mylar (ratio of ingredients by volume)	Attenuation upon transmission (dB)	Attenuation upon reflection (dB)	Resistivity (Ωcm)
10	Base paint + nickel powder II (100 : 10)	16.2 ± 0.5	3.9 ± 0.1	8.3 ± 0.3
11	Base paint + nickel powder II (100 : 20)[b]	26.2 ± 0.6	1.8 ± 0.1	4.7 ± 0.3
12	Base paint + nickel powder II + mumetal (100 : 20 : 2)	29.3 ± 0.5	1.9 ± 0.1	4.9 ± 0.4

[a] From DuPont's datasheet for Mylar.
[b] Maximum possible filler content.

Table 1 EMI shielding effectiveness (attenuation upon transmission), attenuation upon reflection and electrical resistivity. (cont'd)

Row No.	Material on Mylar (ratio of ingredients by volume)	Attenuation upon transmission (dB)	Attenuation upon reflection (dB)	Resistivity (Ωcm)
13	Base paint + nickel flake (100 : 10)	25.7 ± 0.6	2.6 ± 0.2	4.3 ± 0.3
14	Base paint + nickel flake (100 : 20)[b]	32.4 ± 0.5	1.5 ± 0.1	3.4 ± 0.2
15	Base paint + nickel flake + mumetal (100 : 20 : 2)	38.5 ± 0.7	1.6 ± 0.1	3.5 ± 0.3

[a] From DuPont's datasheet for Mylar.
[b] Maximum possible filler content.

- Design an aircraft that cannot be detected by radar.
- We might make the aircraft from materials that are transparent to radar. Many polymers, polymer-matrix composites, and ceramics satisfy this requirement.
- We might design the aircraft so that the radar signal is reflected at severe angles from the source.
- The internal structure of the aircraft also can be made to absorb the radar. For example, use of a honeycomb material in the wings may cause the radar waves to be repeatedly reflected within the material.
- We might make the aircraft less visible by selecting materials that have electronic transitions of the same energy as the radar.

Table 5.1 Electrical resistivity (DC), absolute thermoelectric power (20-65°C) and EMI shielding effectiveness (1 GHz, coaxial cable method) of cement pastes containing various electrically conductive admixtures.

Conductive admixture	Vol. %	Resistivity (Ω.cm)	Absolute thermoelectric power (μV/°C)[a]	EMI shielding effectiveness (dB)
None	0	6.1×10^5	-2.0	4
None, but with graphite powder (<1 μm) coating	/	/	/	14
Steel fiber[43] (8 μm diameter)	0.09	4.5×10^3	/	19
Steel fiber[44] (60 μm diameter)	0.10	5.6×10^4	-57	/
Steel fiber[43] (8 μm diameter)	0.18	1.4×10^3	+5[b]	28
Steel fiber[44] (60 μm diameter)	0.20	3.2×10^4	-68	/
Steel fiber[43] (8 μm diameter)	0.27	9.4×10^2	/	38
Steel fiber[44] (60 μm diameter)	0.28	8.7×10^3	0	/
Carbon fiber[37] (10 μm diameter) (crystalline, intercalated)	0.31	6.7×10^3	+12	/
Steel fiber[43] (8 μm diameter)	0.36	57	/	52
Steel fiber[44] (60 μm diameter)	0.40	1.7×10^3	+20	12[b]
Carbon fiber[37] (10 μm diameter) (crystalline, pristine)	0.36	1.3×10^4	-0.5	/
Steel fiber[43] (8 μm diameter)	0.54	23	/	/
Steel fiber[44] (60 μm diameter)	0.50	1.4×10^3	+26	/
Carbon fiber[37] (15 μm diameter) (amorphous, pristine)	0.48	1.5×10^4	-0.9	/
Carbon filament[24] (0.1 μm diameter)	0.5	1.3×10^4	/	30
Graphite powder[73] (<1 μm)	0.46	2.3×10^5	/	10
Coke powder[33] (< 75 μm)	0.51	6.9×10^4	/	44
Steel fiber[43] (8 μm diameter)	0.72	16	/	59
Steel fiber[43] (8 μm diameter)	0.90	40	/	58
Carbon fiber[37] (15 μm diameter) (amorphous, pristine)	1.0	8.3×10^2	+0.5	15[c]
Carbon fiber[37] (10 μm diameter) (crystalline, intercalated)	1.0	7.1×10^2	+17	/
Carbon filament[24] (0.1 μm diameter)	1.0	1.2×10^4	/	35
Graphite powder[73] (<1 μm)	0.92	1.6×10^5	/	22
Coke powder[33] (< 75 μm)	1.0	3.8×10^4	/	47
Steel dust (0.55 mm)	6.6	/	/	5[b]
Graphite powder[30] (< 45 μm)	37	4.8×10^2	+20	/

[a] Seebeck coefficient (with copper as the reference) minus the absolute thermoelectric power of copper. The Seebeck coefficient (with copper as the reference) is the voltage difference (hot minus cold) divided by the temperature difference (hot minus cold).
[b] Ref. 72.
[c] 0.84 vol.% carbon fiber in cement mortar at 1.5 GHz[74].