

# Materiais Eléctricos e Magnéticos para Engenharia

**Professor: Marcus V. Batistuta**

Aula-7

Propriedades Eléctricas e Magnéticas da Matéria

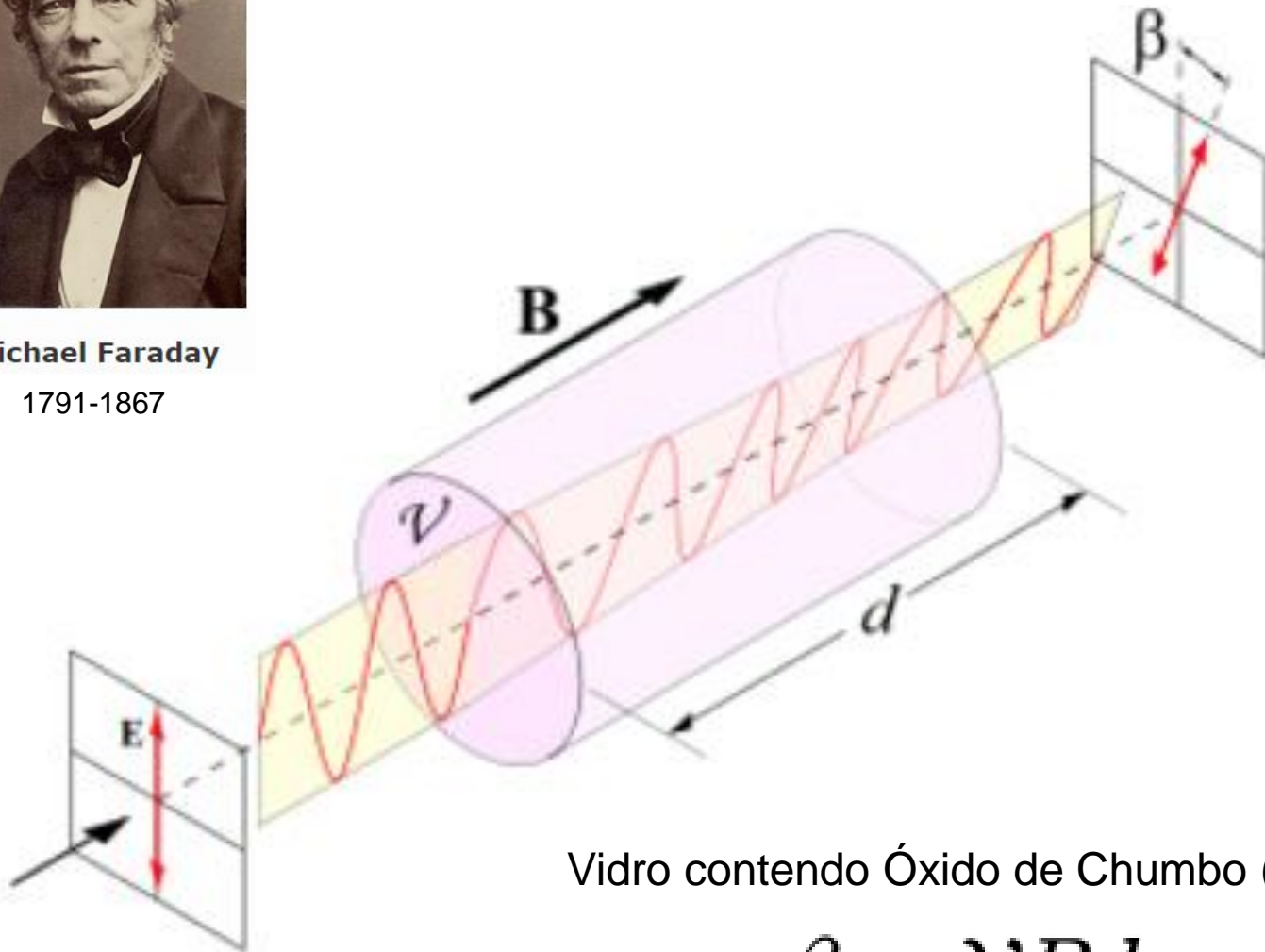
1º Semestre de 2018

**FGA - Universidade de Brasília**



Michael Faraday  
1791-1867

## Efeito de Faraday (1845)



Vidro contendo Óxido de Chumbo (PbO)

$$\beta = \nu B d$$

# Campos Eletromagnéticos x Matéria

## Equações de Maxwell do Eletromagnetismo

$$\begin{array}{ll} \text{Gauss:} & \left\{ \begin{array}{l} \nabla \cdot \mathbf{D} = \rho \\ \nabla \cdot \mathbf{B} = 0 \end{array} \right. & \left( \nabla^2 - \mu\epsilon \frac{\partial^2}{\partial t^2} \right) \mathbf{E} = 0 \\ \text{Faraday:} & \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} & \left( \nabla^2 - \mu\epsilon \frac{\partial^2}{\partial t^2} \right) \mathbf{B} = 0 \\ \text{Ampère:} & \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} & \\ & & c = \frac{1}{\sqrt{\mu\epsilon}} \end{array}$$

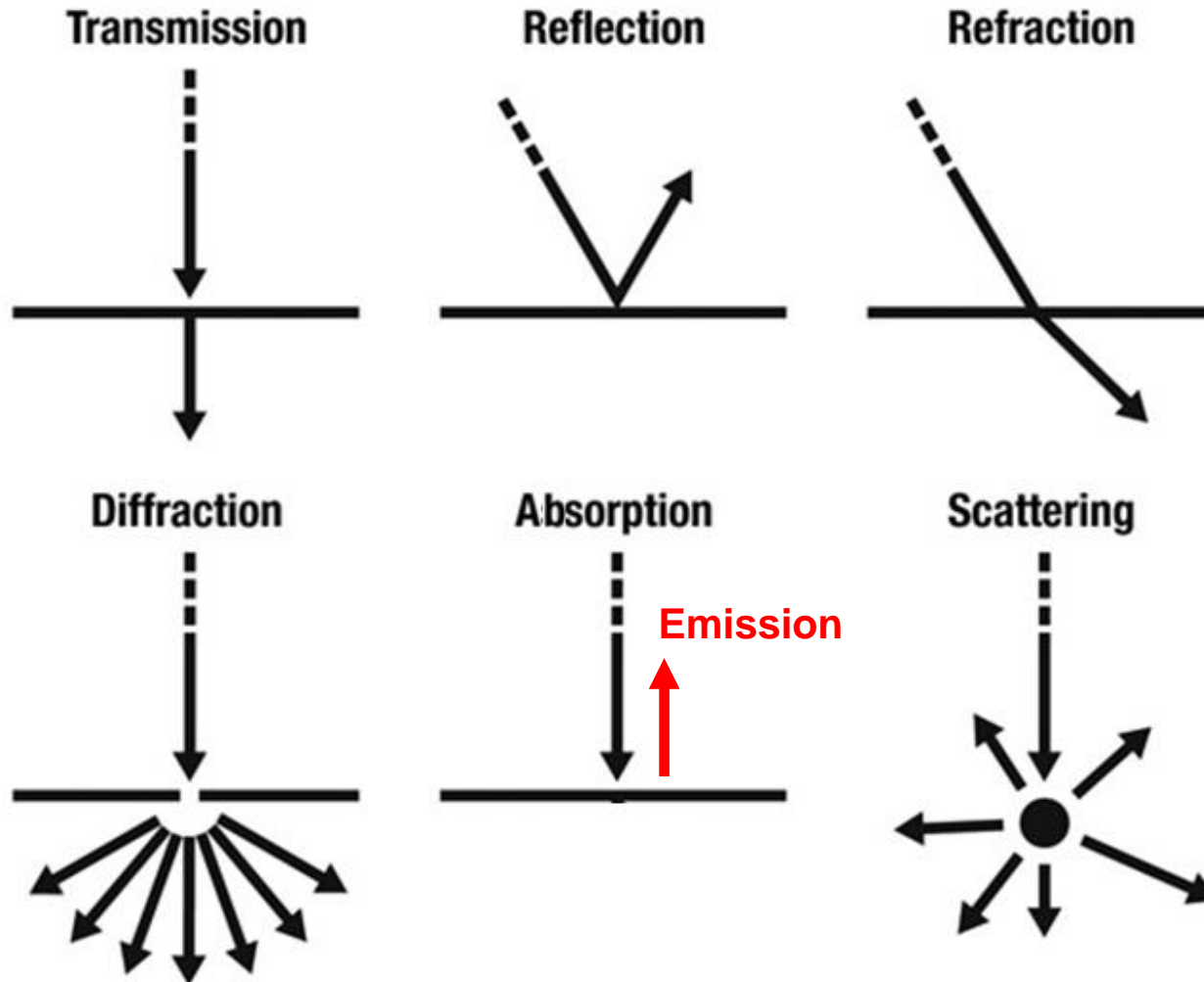
$$\text{Continuidade: } \nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t}$$

$$\text{Lorentz: } \vec{F} = q \left[ \vec{E} + \vec{v} \times \vec{B} \right]$$

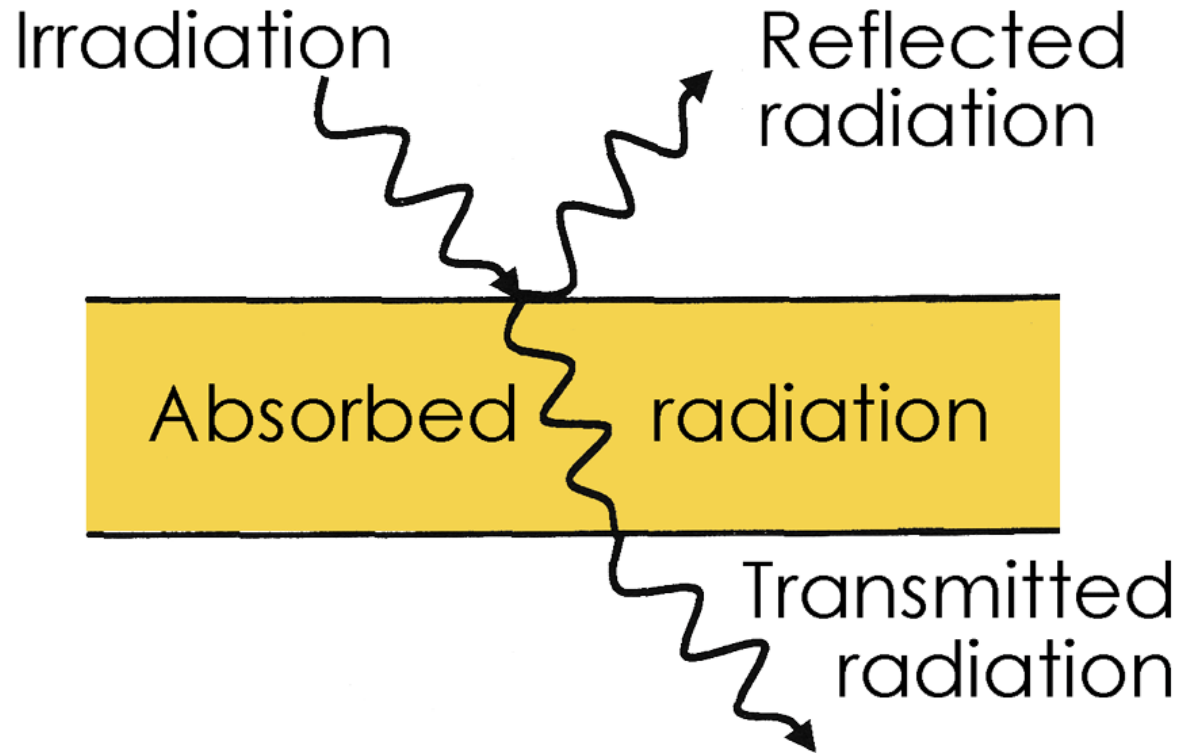
$$\vec{E} = \epsilon \vec{D}$$

$$\vec{B} = \mu \vec{H}$$

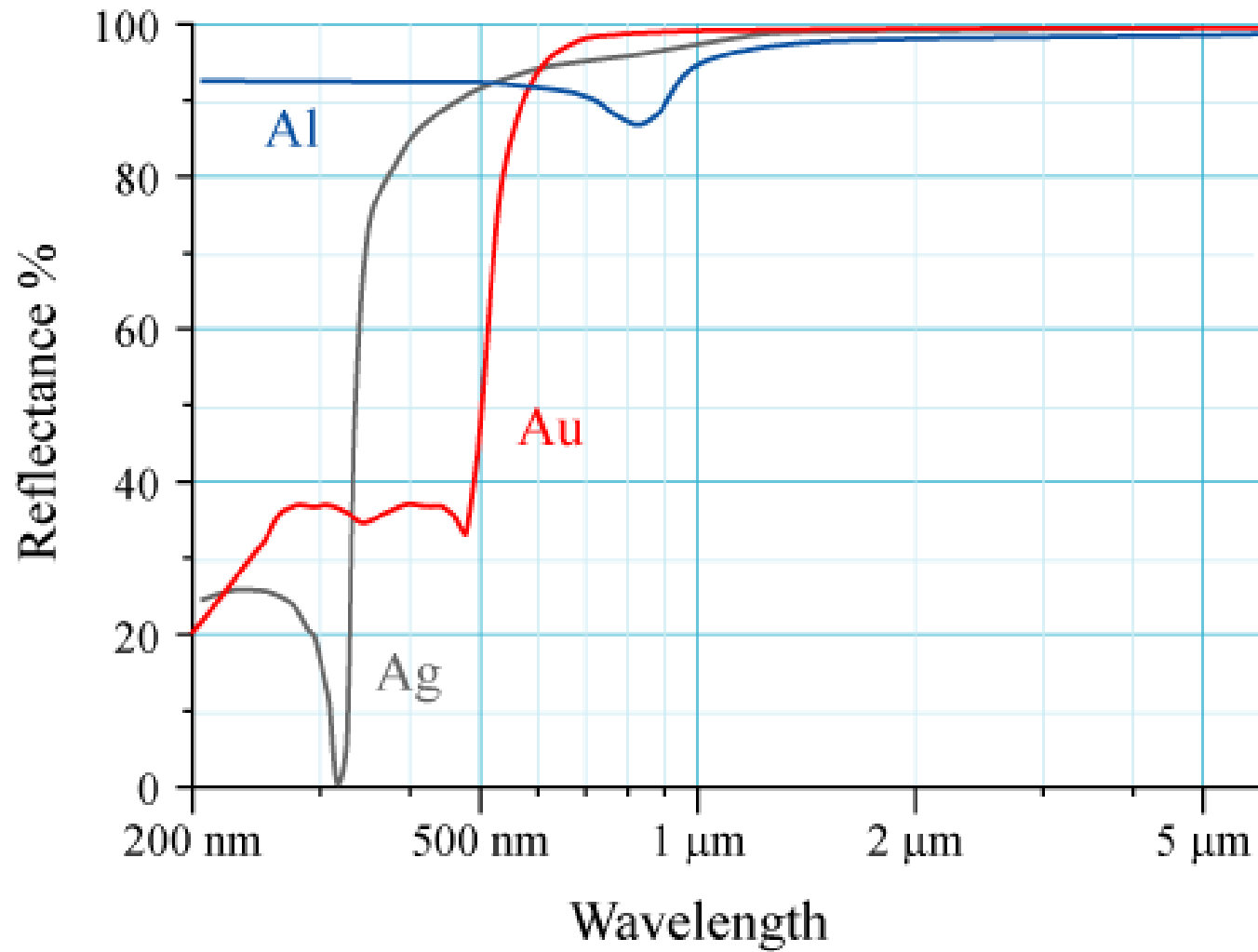
# Interação de Fótons com a Matéria



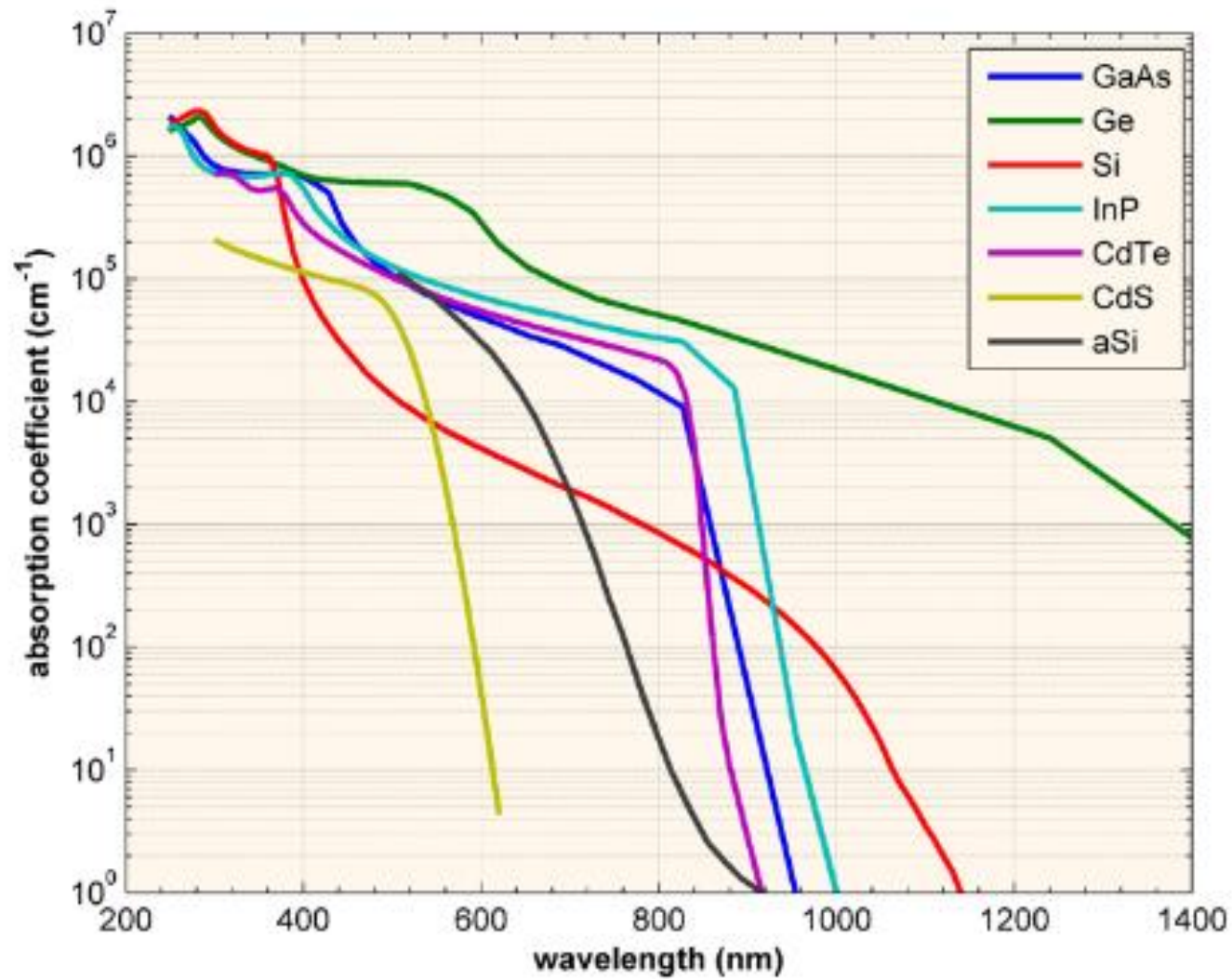
# Reflexão, Absorção e Transmissão



# Refletividade de Metais



# Absorção em Semicondutores



$$I(x, \lambda) = I_0 e^{-\alpha(\lambda) \cdot x} [W / m^2]$$

## Propriedades de Materiais Dielétricos

$$\vec{D} = \epsilon_0 \vec{\mathcal{E}} + \vec{P}$$

$$\epsilon_0 = (4\pi \times 9 \times 10^9)^{-1} \text{C}^2/\text{Nm}^2$$

$\text{C}^2/\text{Nm}^2$  é equivalente ao farad/metro

Susceptibilidade:  $\chi = \frac{P}{\epsilon_0 \mathcal{E}} \qquad \epsilon = \frac{D}{\mathcal{E}}$

$$\epsilon = \epsilon_0(1 + \chi)$$



## Propriedades de Materiais Dielétricos

Material	$\epsilon$	$\mathcal{E}_r (10^6 \text{ V/m})$
Baquelite	4,8	12
Mica	5,4	160
Óxido de alumínio ( $Al_2O_3$ )	10	
Óxido de tântalo ( $Ta_2O_5$ )	28	100
Óxido de Titânio ( $TiO_3$ )	94	6
Papel	3,5	14
Porcelana	6,5	4
Quartzo fundido ( $SiO_2$ )	3,8	8
Teflon (PFTE)	1,9	60

Tabela 10.1: Permissividade relativa  $\epsilon = \epsilon/\epsilon_0$  em baixas frequências e rigidez dielétrica  $\mathcal{E}_r$  de alguns materiais dielétricos à temperatura ambiente.

## Propriedades de Materiais Dielétricos

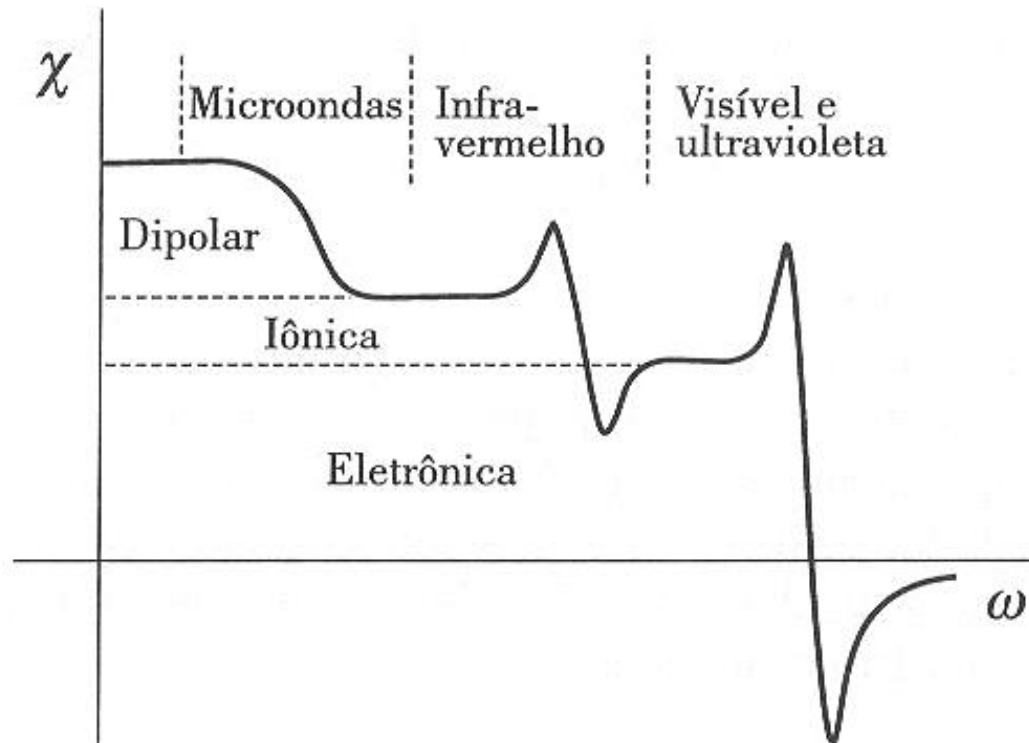


Figura 10.2: Variação da susceptibilidade de um dielétrico com a frequência do campo aplicado.

## Materiais Dielétricos Ferroelétricos

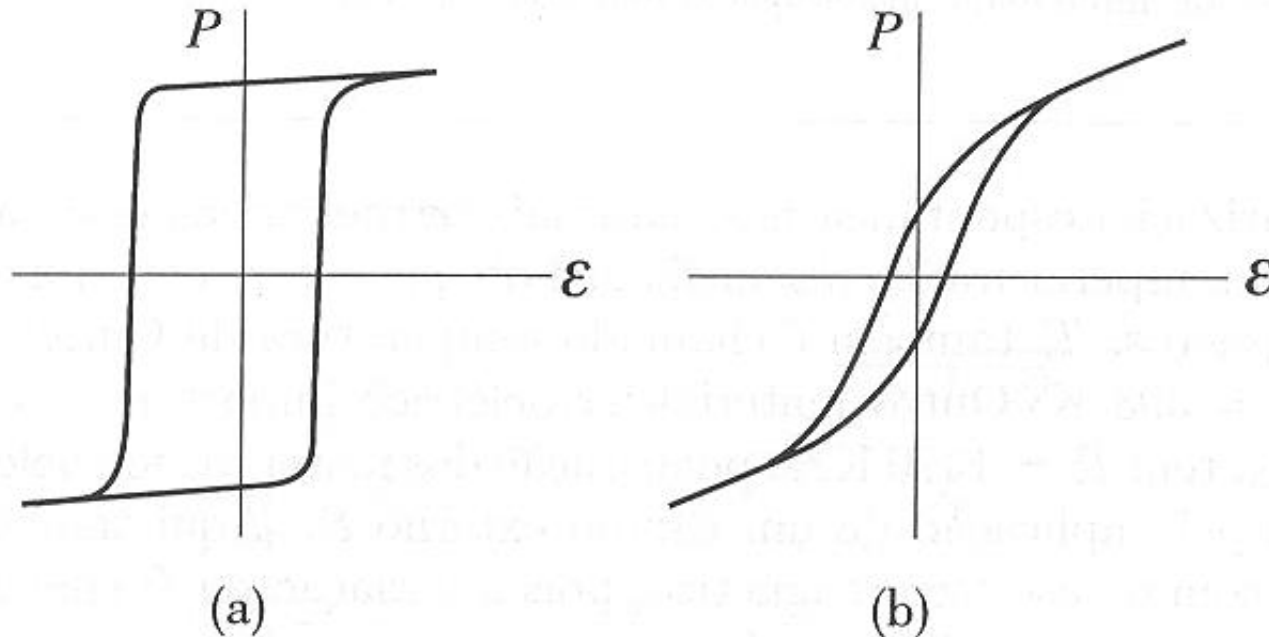
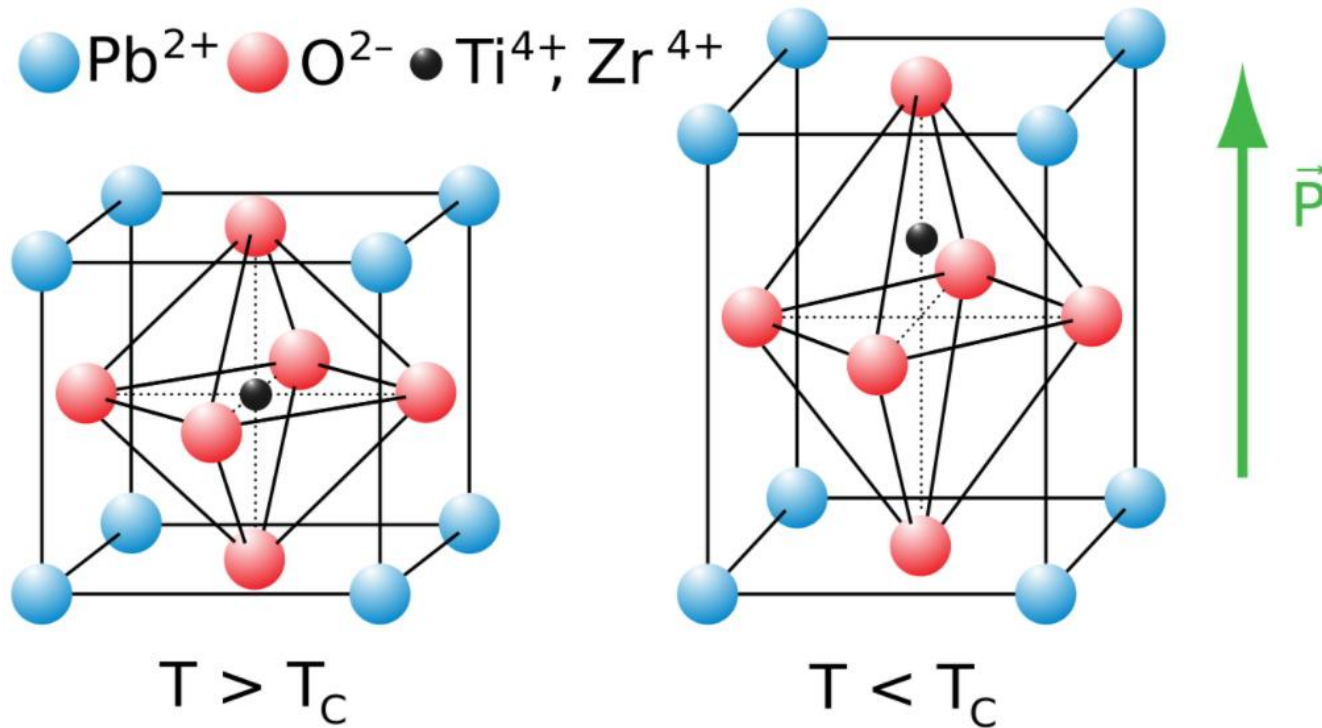


Figura 10.11: Ciclos de histerese de materiais ferroelétricos: (a) ciclo retangular observado em cristais; (b) ciclo alongado em cerâmicas policristalinas alinhadas.

# Titanato zirconato de chumbo (PZT)

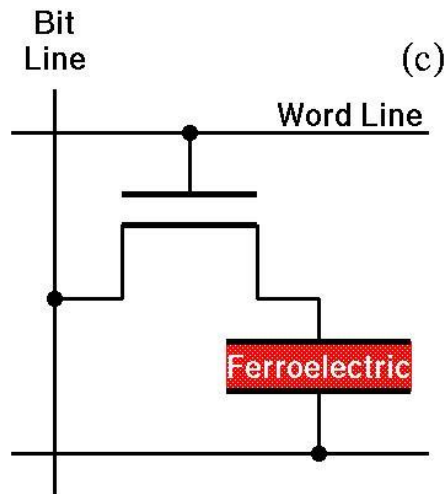
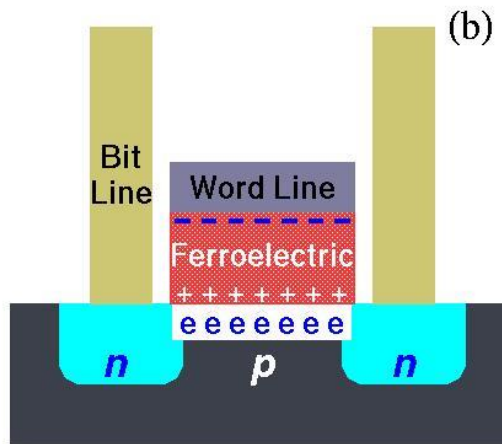
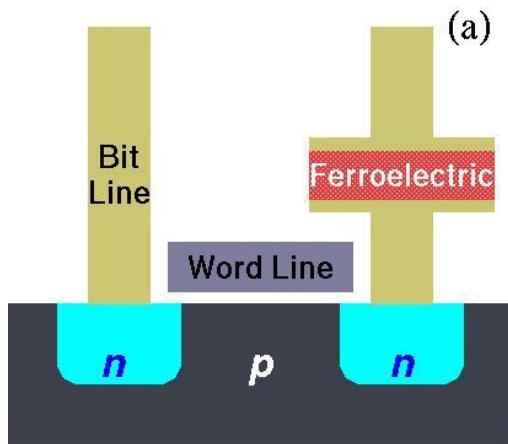
## *Lead zirconate titanate*



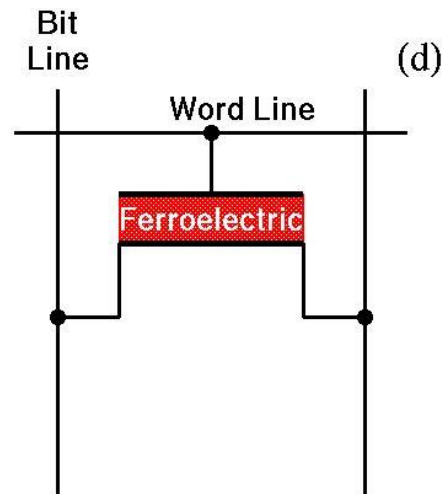
**Ferroeletricidade, Piezoeletricidade e Piroeletricidade**

**Família das Perovskitas**

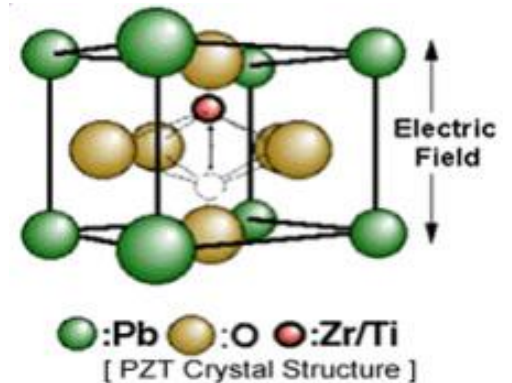
# Memórias Ferroelétricas (FRAM)



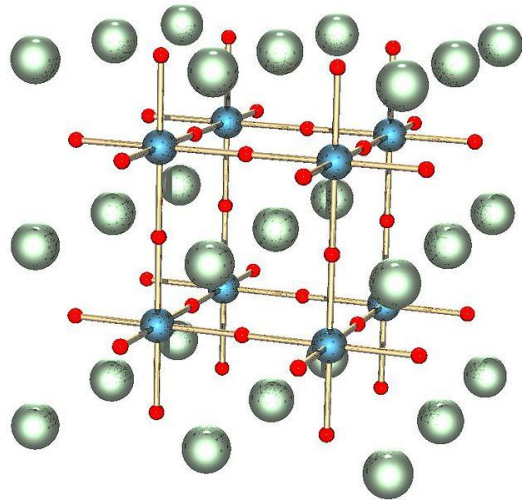
1T1C type



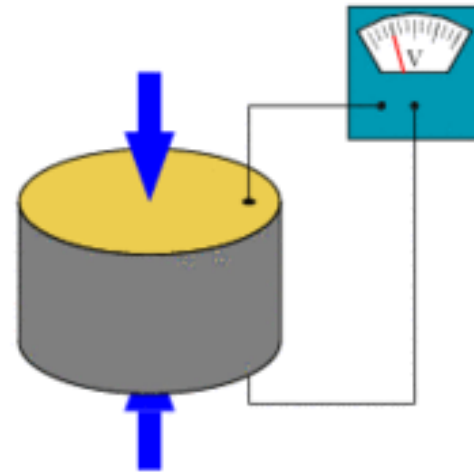
1T type



# Materiais Piezoelétricos



$\text{BaTiO}_3$



Efeito Piezoelétrico (1880)



Tweeter



Jacques e Pierre Curie

# Modelo para Materiais Piezoelétricos

## ◆ Direct Effect

$$\begin{matrix} 3 \times 1 & & 3 \times 6 & 6 \times 1 \\ (P) & = & (d) & (\sigma) \end{matrix}$$

Matrix form

$$P_i = d_{ijk} \sigma_{jk}$$

Tensor form

Units:

$$\frac{C}{N} = \left( \frac{C}{N} \right) \left( \frac{J}{J} \right) = \left( \frac{C}{N} \right) \left( \frac{N \cdot m}{C \cdot V} \right) = \frac{m}{V}$$

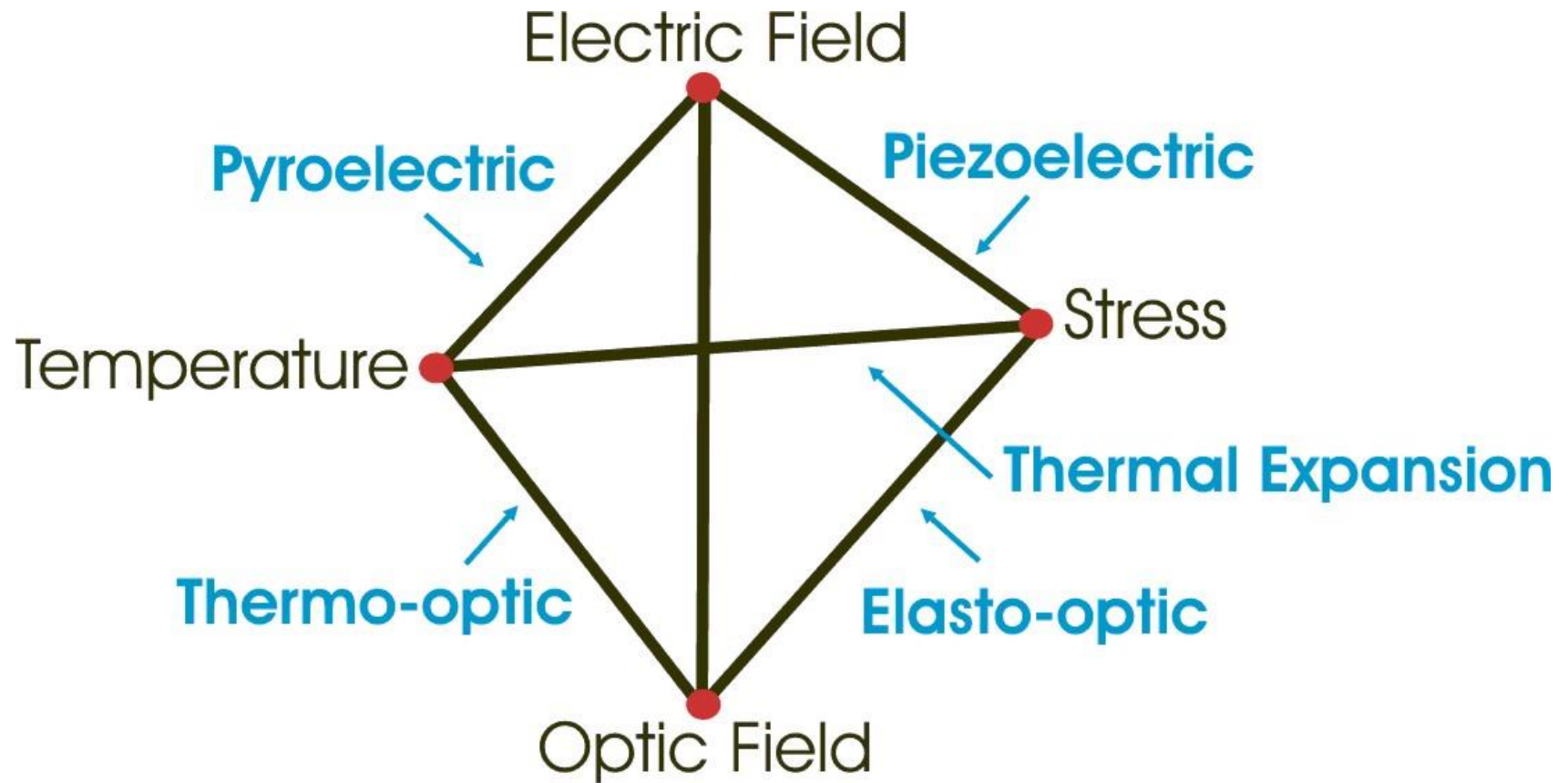
## ◆ Converse Effect

$$\begin{matrix} 6 \times 1 & & 6 \times 3 & 3 \times 1 \\ (\varepsilon) & = & (d)^t & (E) \end{matrix}$$

$$\varepsilon_{jk} = d_{ijk} E_i$$



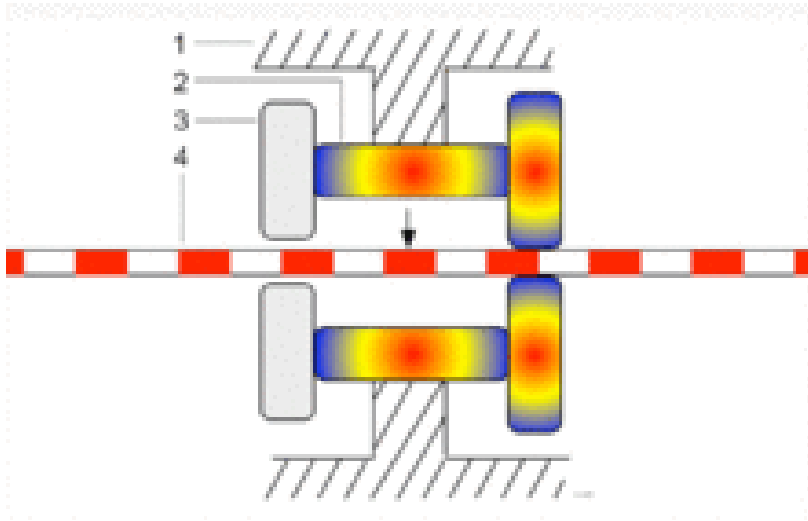
# Efeitos da Matéria vs. Energia



[http://www.physics.rutgers.edu/~karin/601/Solid\\_State\\_Physics\\_I\\_\\_Lecture\\_1.html](http://www.physics.rutgers.edu/~karin/601/Solid_State_Physics_I__Lecture_1.html)



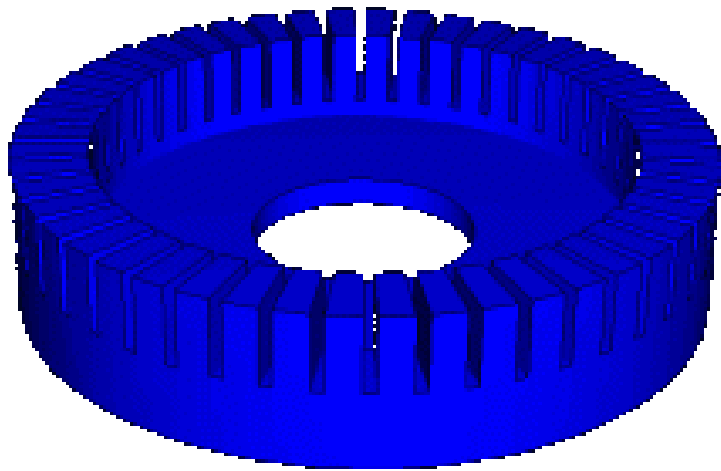
# Motores Piezoelétricos



“Inchworm”



# Motores Piezoelétricos

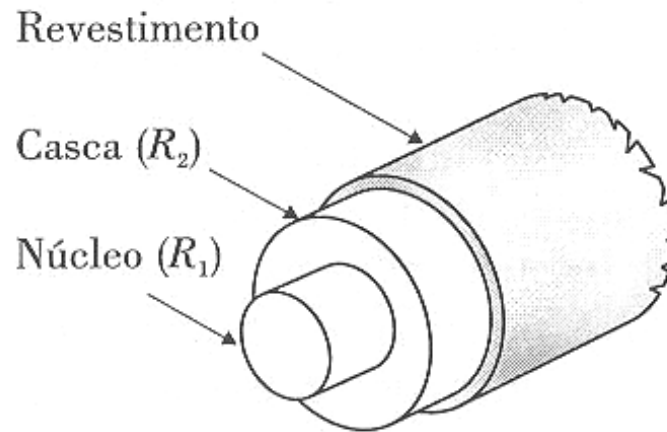


**Traveling Wave**

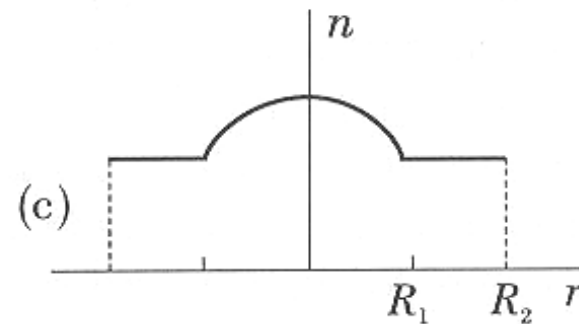
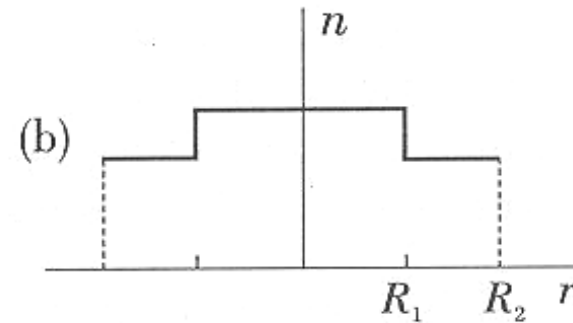


# Fibra Ótica

$$n_i = \frac{c}{v_i} = \frac{1/\sqrt{\mu_0 \epsilon_0}}{1/\sqrt{\mu_i \epsilon_i}}$$



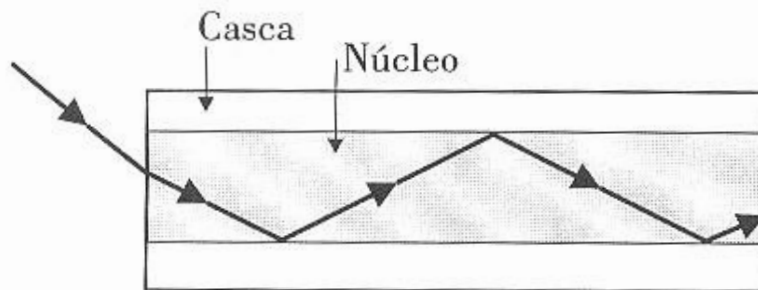
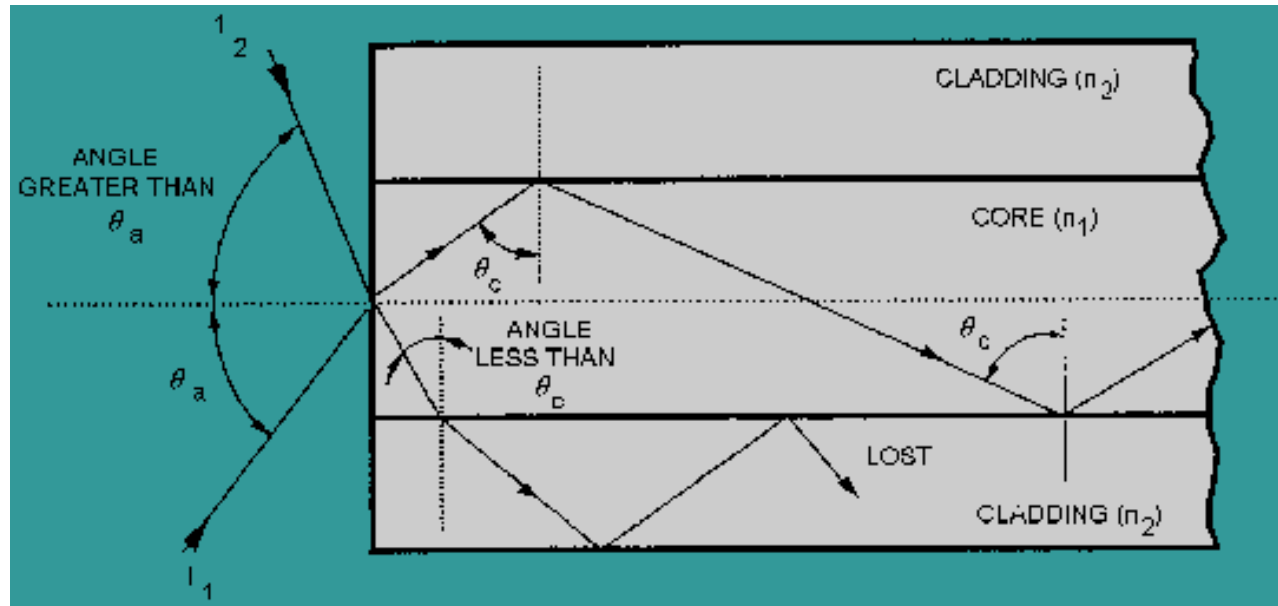
(a)



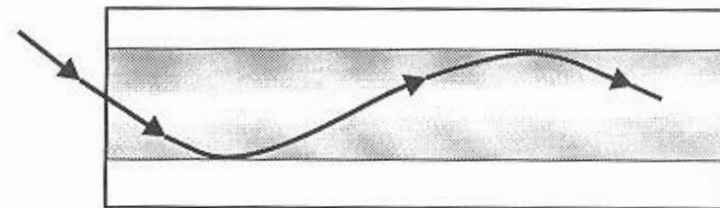
(c)

Figura 8.51: (a) Seção de uma fibra óptica mostrando o núcleo, a casca e o revestimento; (b) perfil de índice de refração em degrau; (c) perfil gradual.

# Propagação em Fibra Ótica



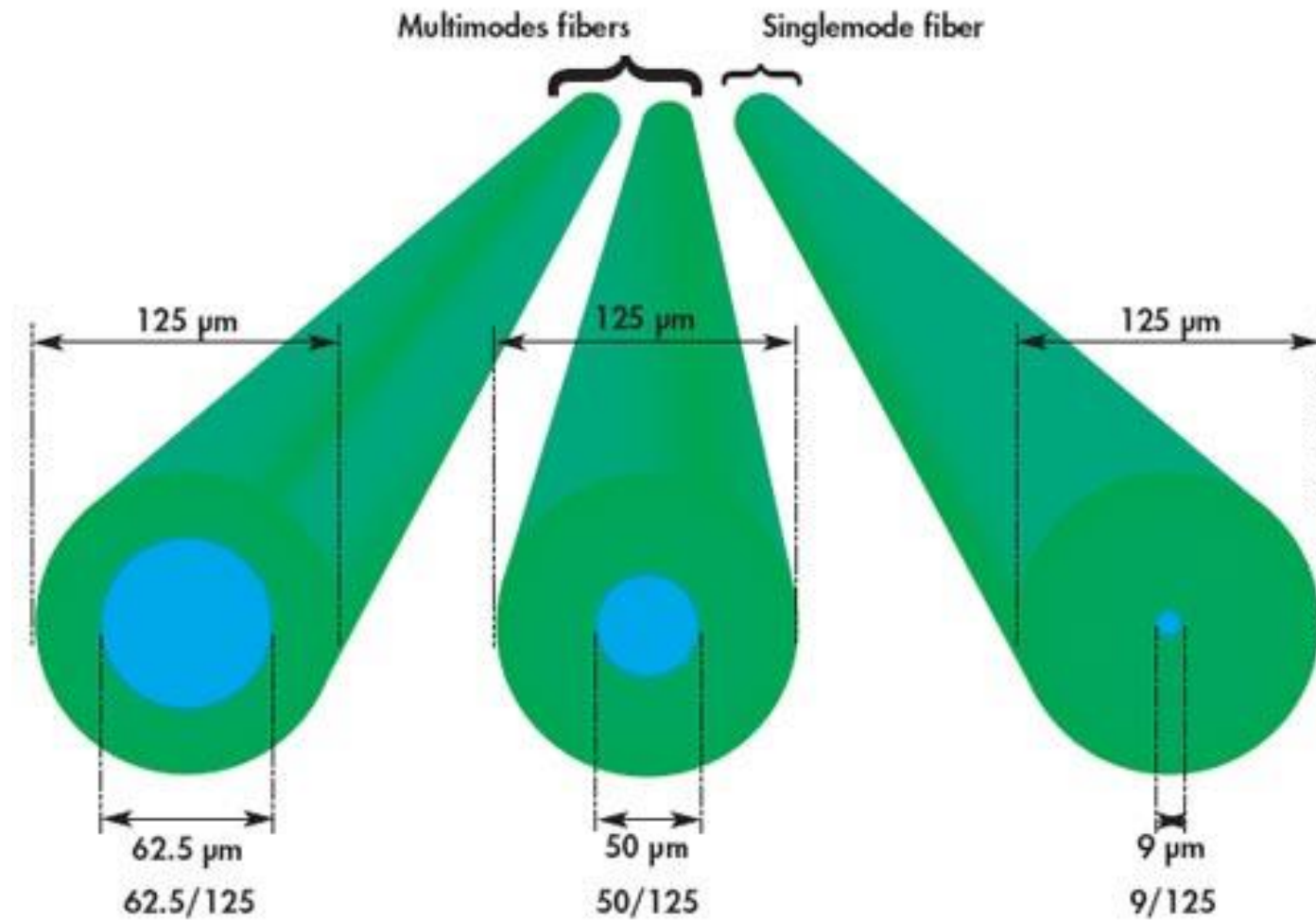
(a)



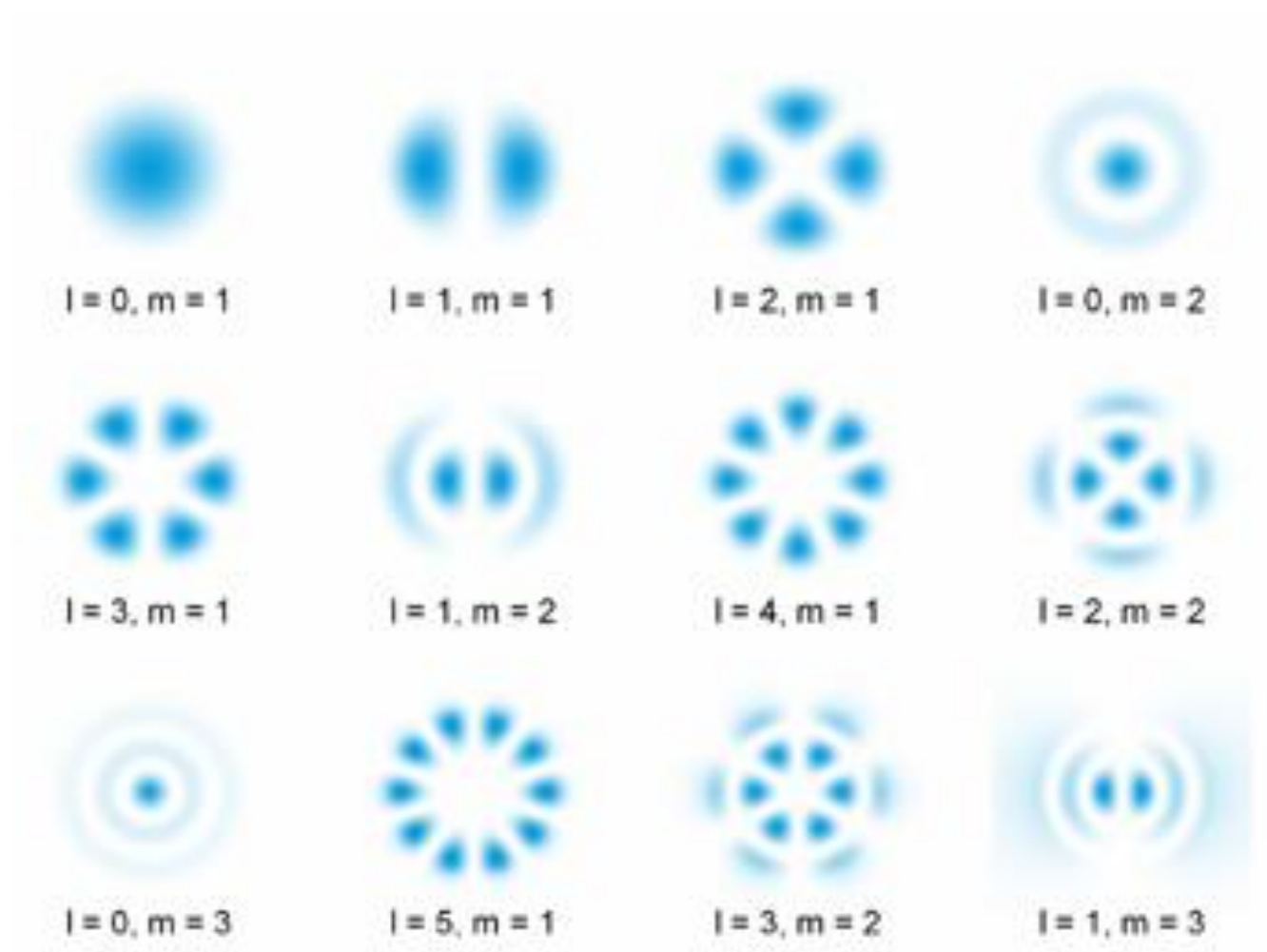
(b)

Figura 8.52: Ilustração da propagação da luz em fibras ópticas: (a) perfil em degrau; (b) perfil gradual.

# Dimensões de Fibras Óticas



# Modos de Propagação em Fibras Óticas



# Atenuação em Fibra Ótica

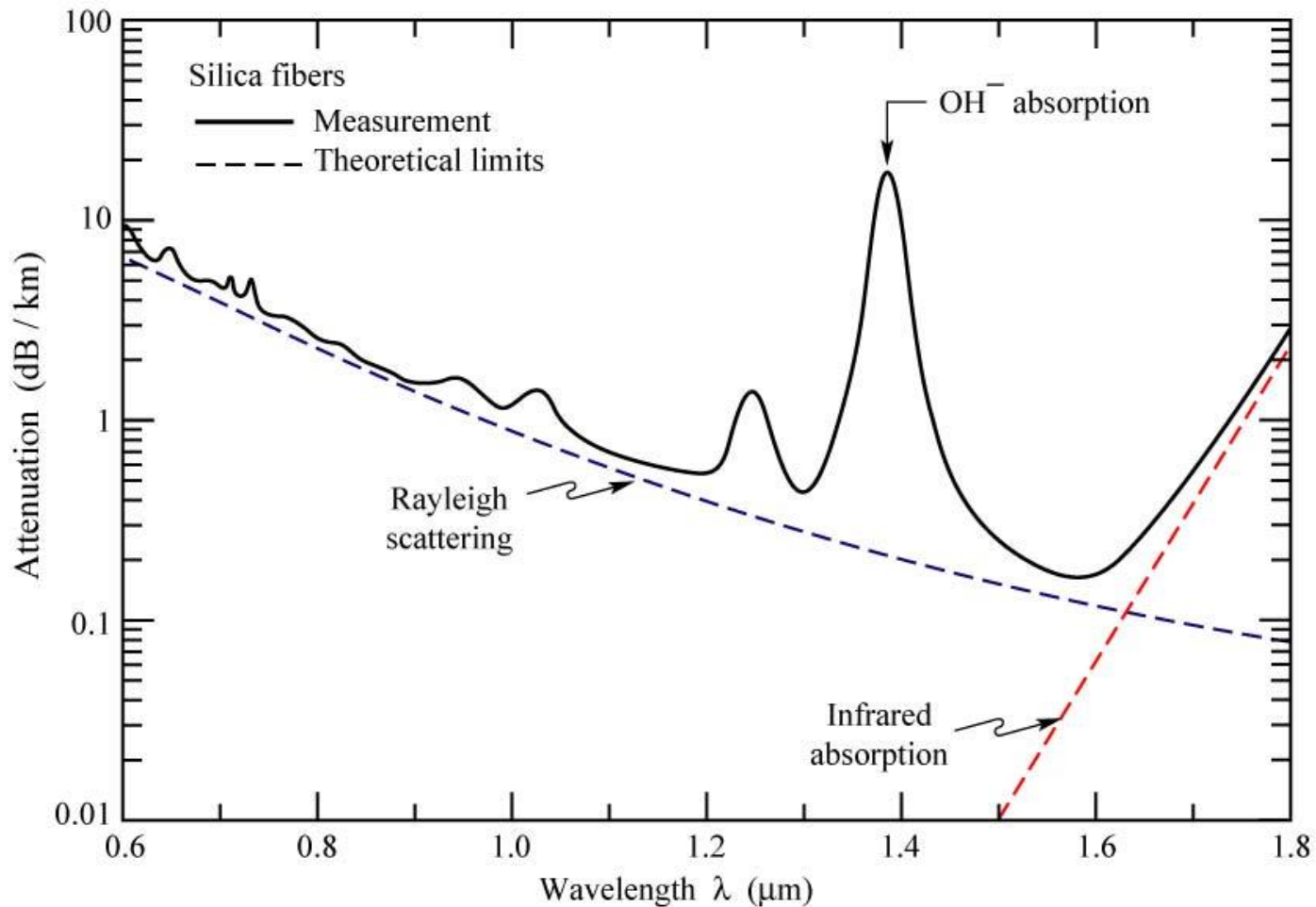
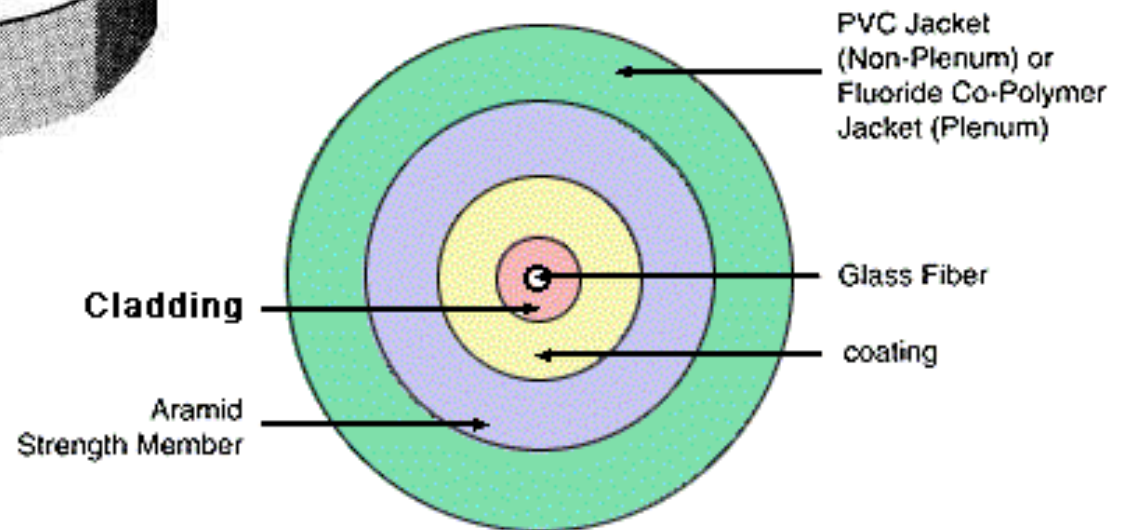
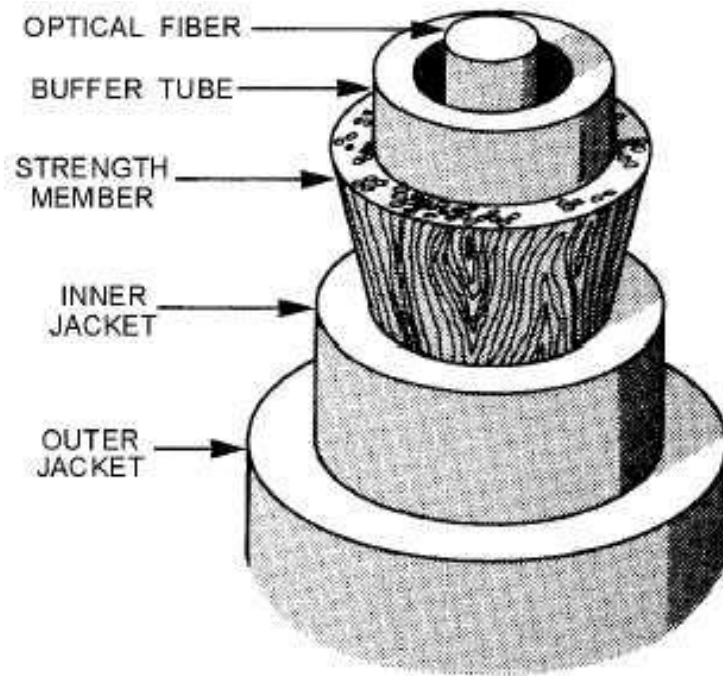


Fig. 22.2. Measured attenuation in silica fibers (solid line) and theoretical limits (dashed lines) given by Rayleigh scattering in the short-wavelength region, and by molecular vibrations (infrared absorption) in the infrared spectral region.

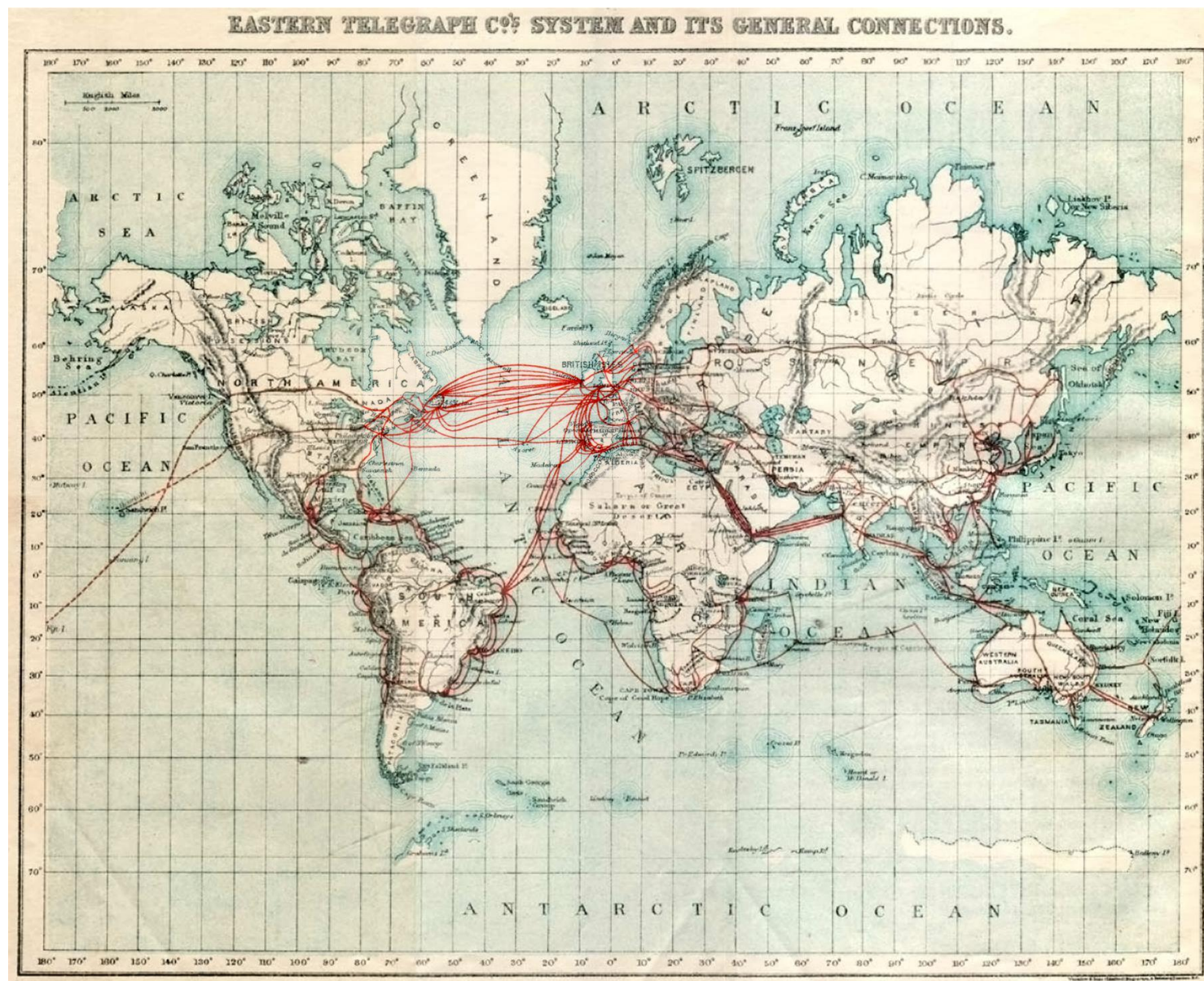
# Cabo de Fibra Ótica





## Cabo Submarino de Fibras Óticas

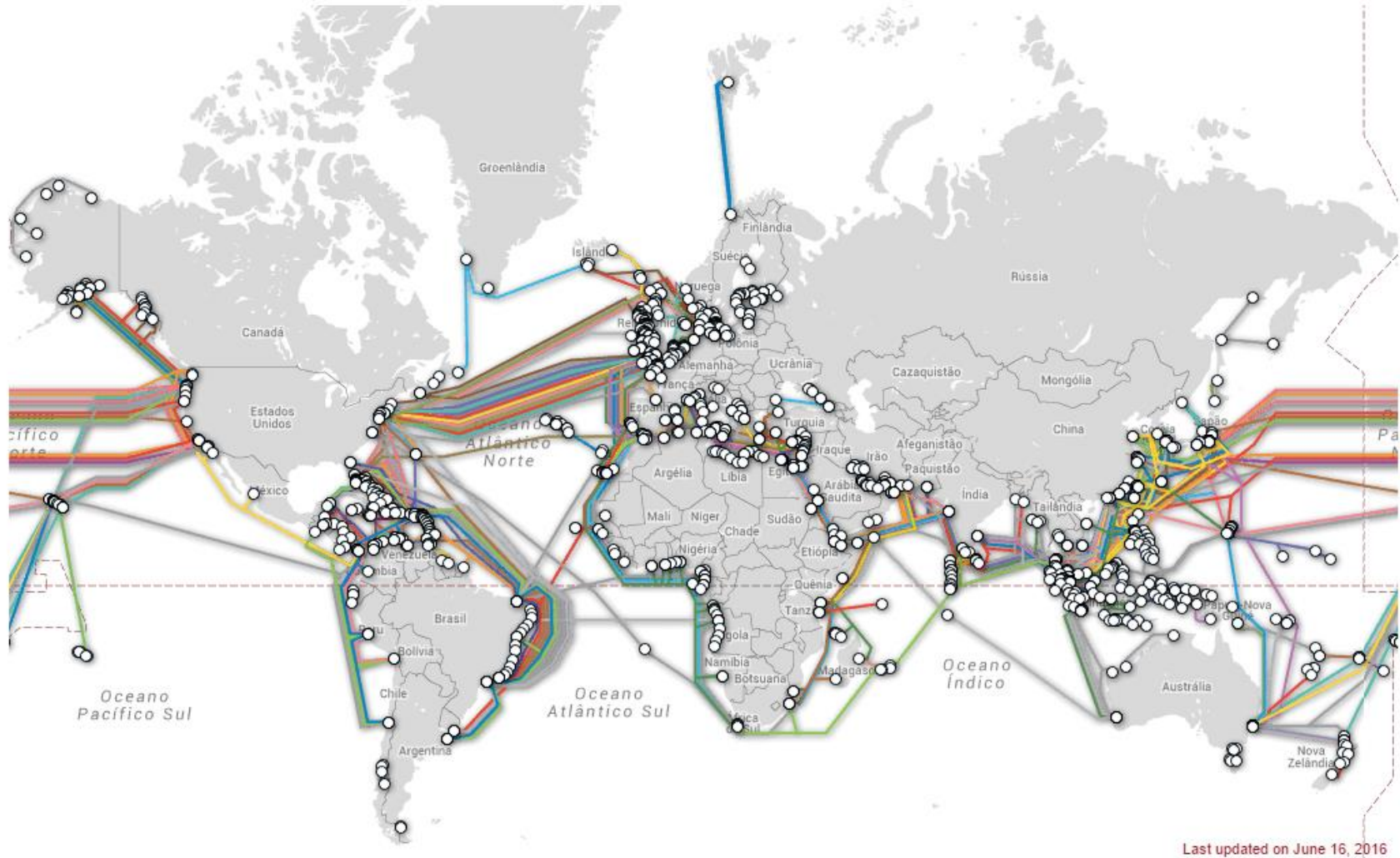




<http://dailyinfographics.eu/locations-of-telegraph-cables-around-the-world-in-1877/>



# Cabos Submarinos de Fibras Óticas



<http://www.submarinecablemap.com/>

# Sistema de Comunicação com Fibra Ótica

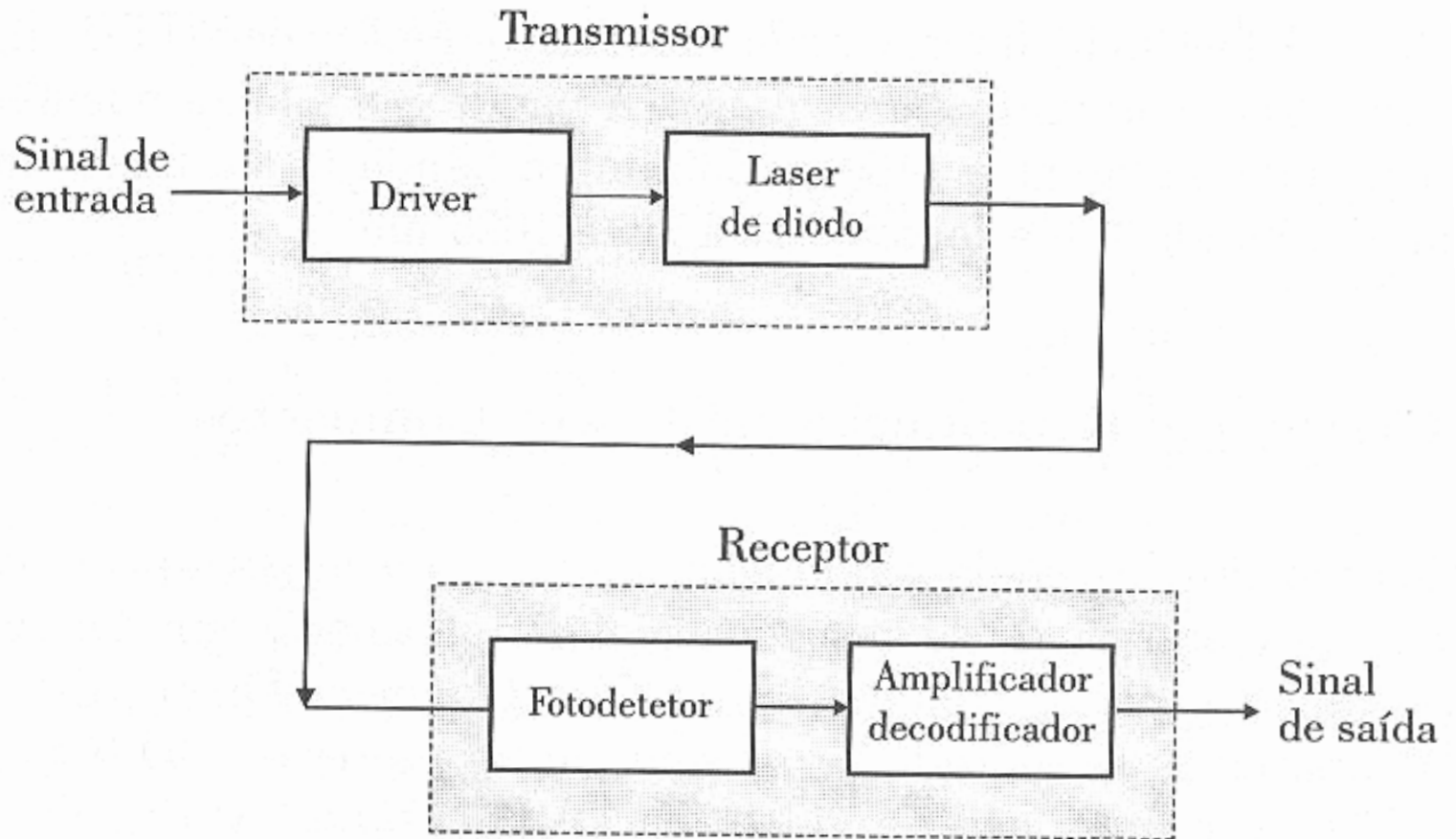
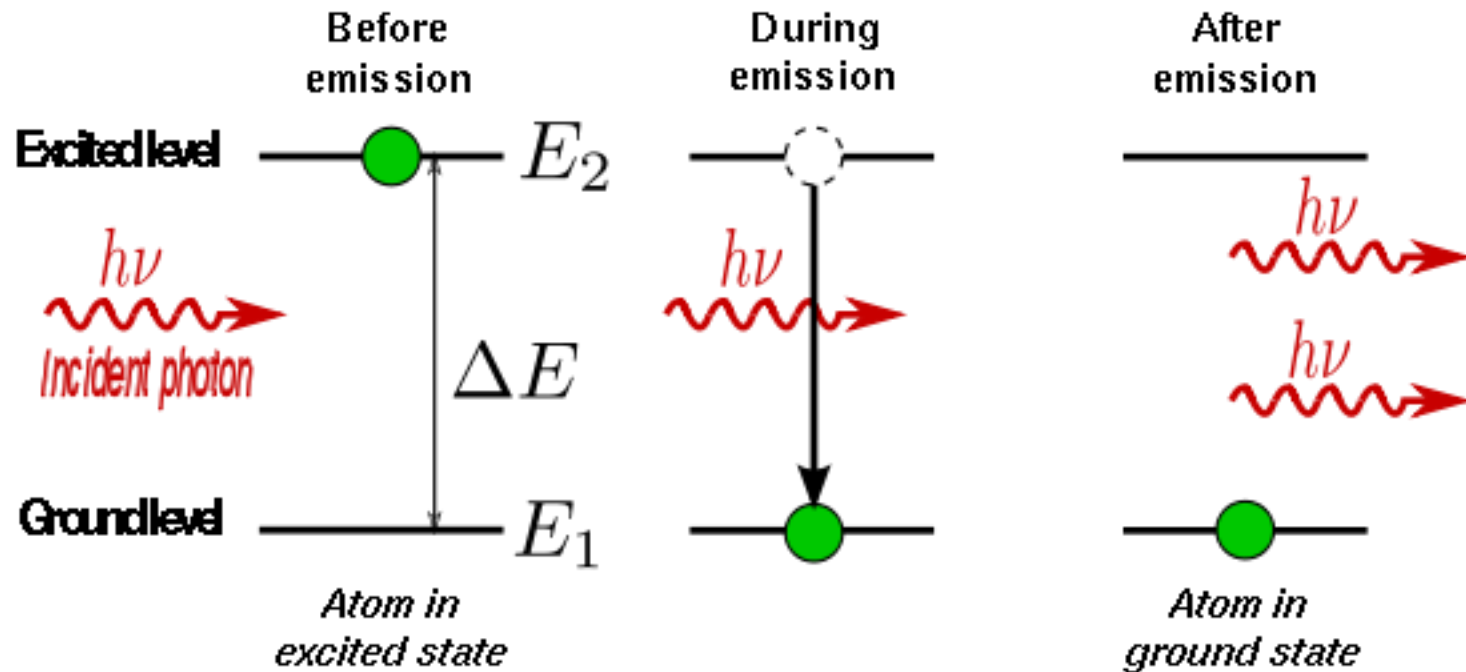


Figura 8.54: Componentes básicos de um sistema de comunicações ópticas.

# LASER

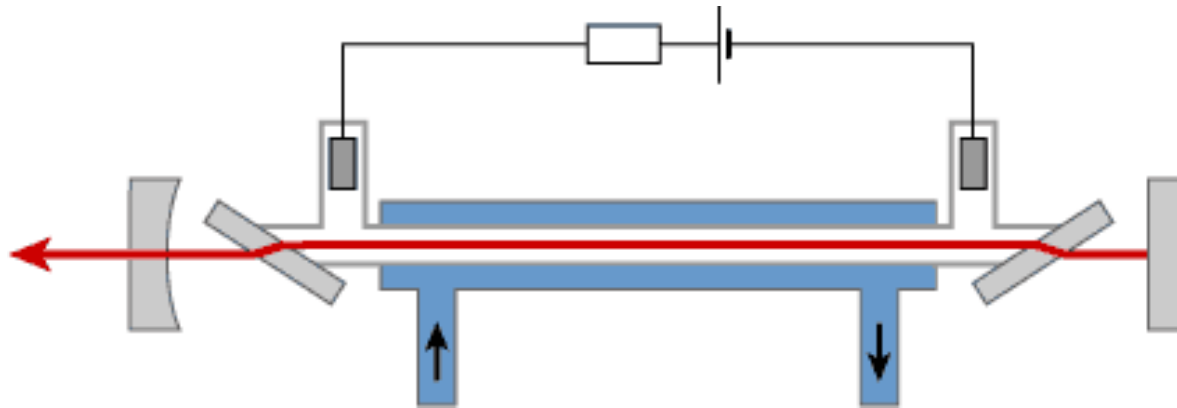
## Light Amplification by Stimulated Emission of Radiation



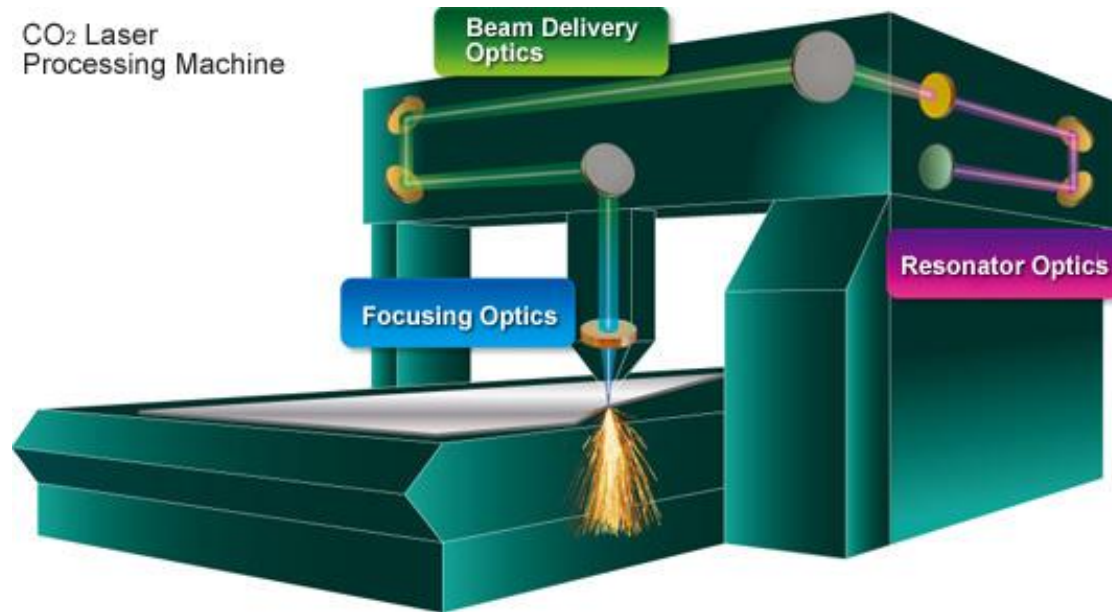
$$E_2 - E_1 = \Delta E = h\nu$$

Einstein, A (1917). *Zur Quantentheorie der Strahlung* (On the Quantum Theory of Radiation)

## LASER em Fase Gasosa / Plasma

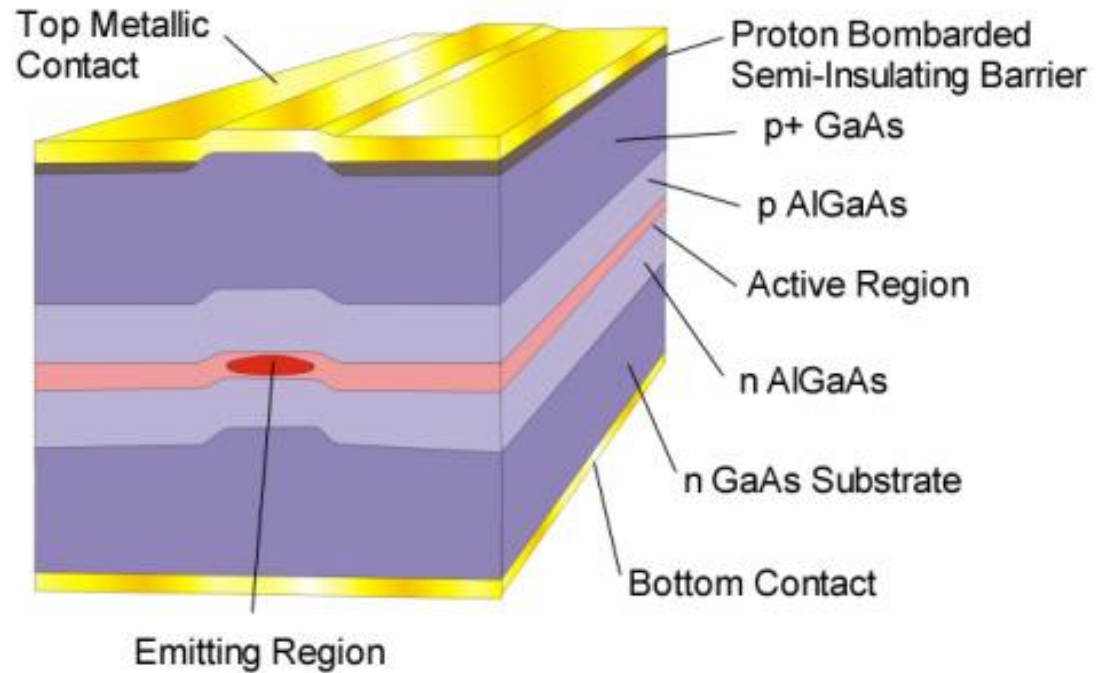


CO<sub>2</sub> Laser  
Processing Machine



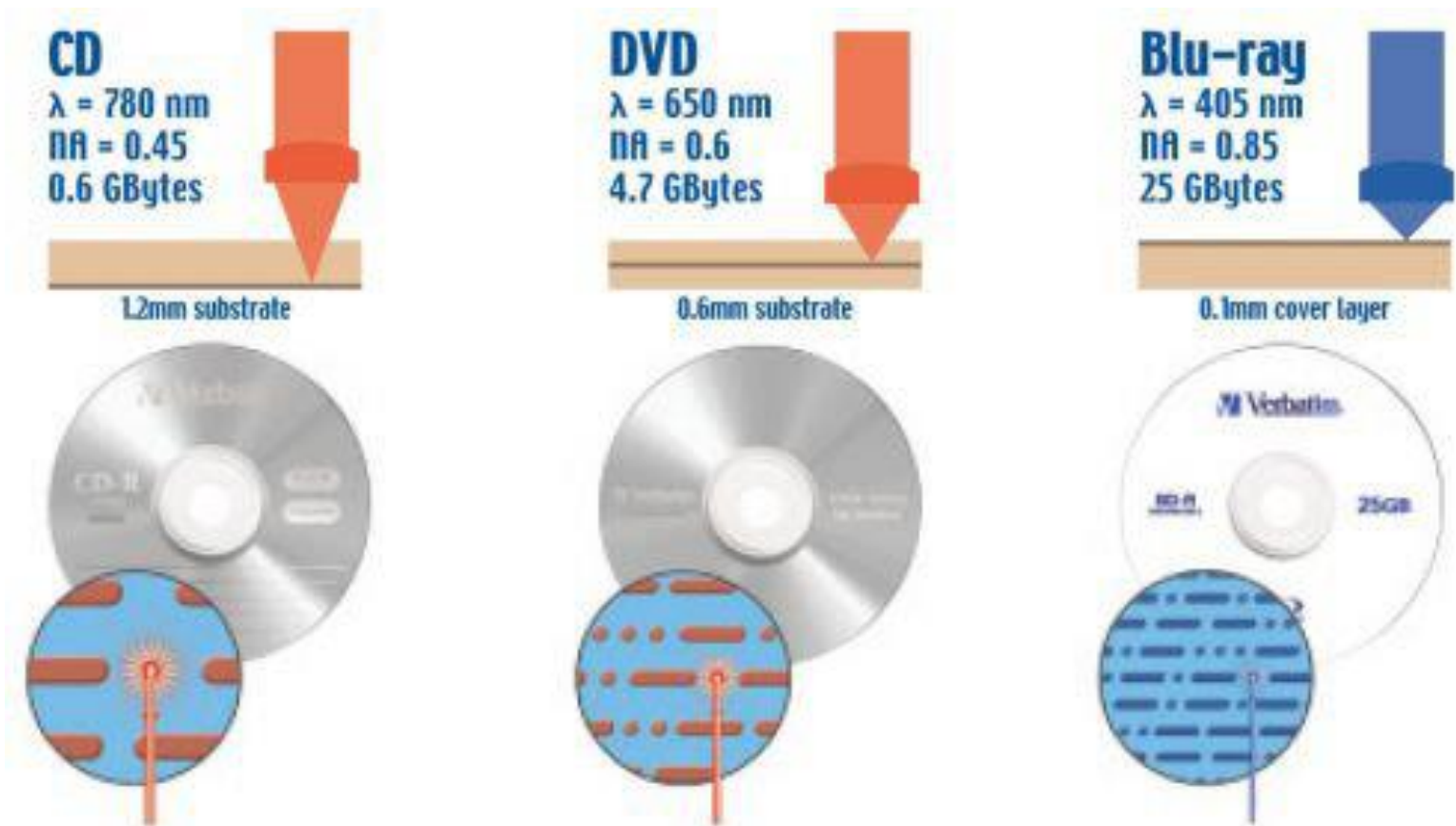
# LASERs Semicondutores

## Light Amplification by Stimulated Emission of Radiation



**Diodo LASER**

# LASERs em Gravação e Leitura de Mídia Ótica





## Propriedades Magnéticas de Materiais

Grandeza	SI	CGS	Relação
$\Phi$	weber (Wb)	maxwell	$1 \text{ Wb} = 10^8 \text{ maxwells}$
$B$	tesla (T) = Wb/m <sup>2</sup>	gauss (G)	$1 \text{ T} = 10^4 \text{ G}$
$H$	A/m	oersted (Oe)	$1 \text{ A/m} = 4\pi \times 10^{-3} \text{ Oe}$ $= (1/79,58) \text{ Oe}$
$M$	A/m	emu/cm <sup>3</sup>	$1 \text{ A/m} = 10^{-3} \text{ emu/cm}^3$
$\mu$	N/A <sup>2</sup>	adimensional	
$\chi$	adimensional	adimensional	

Tabela 9.1: Unidades das grandezas magnéticas nos Sistemas Internacional (SI) e Gaussiano (CGS).

Susceptibilidade:  $\chi = \frac{M}{H}$

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) \quad \vec{B} = \mu \vec{H}$$

$$\mu = \mu_0(1 + \chi)$$

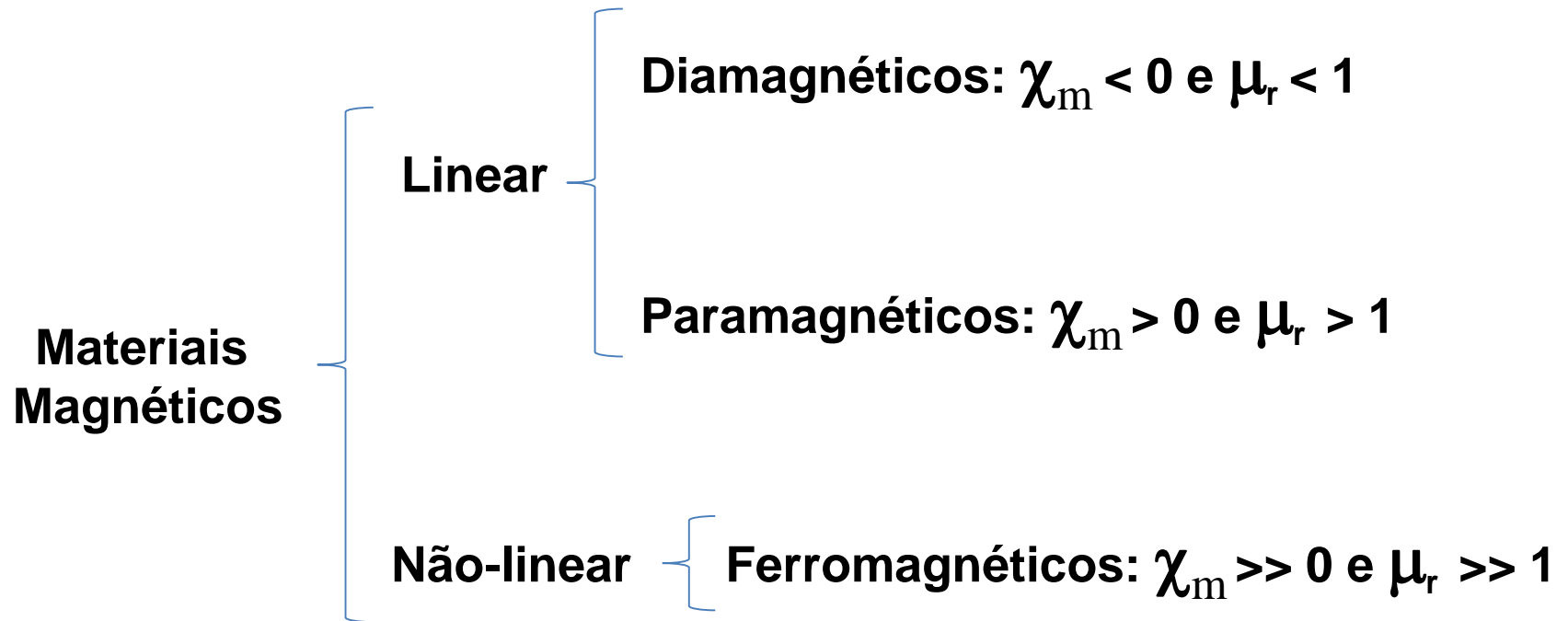
$$\mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2$$

## Propriedades Magnéticas de Materiais

Material	Interaction
Diamagnetic	Is repelled by the applied magnetic field
Paramagnetic	Are attracted by the applied magnetic field with different forces
Ferromagnetic	
Antiferromagnetic	
Ferrimagnetic	

Magnetic Behavior	Value of $\chi$
Diamagnetic	small and negative
Paramagnetic	small and positive
Ferromagnetic	large and positive
Antiferromagnetic	small and positive

# Classificação de Materiais Magnéticos



# Propriedades Magnéticas

1 H																	2 He
3 Li	4 Be																
11 Na	12 Mg																
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac															
			58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	

Ferromagnetic
  Antiferromagnetic

Paramagnetic
  Diamagnetic

## Paramagnetismo

$$\chi \sim 10^{-5} \text{ a } 10^{-3}$$

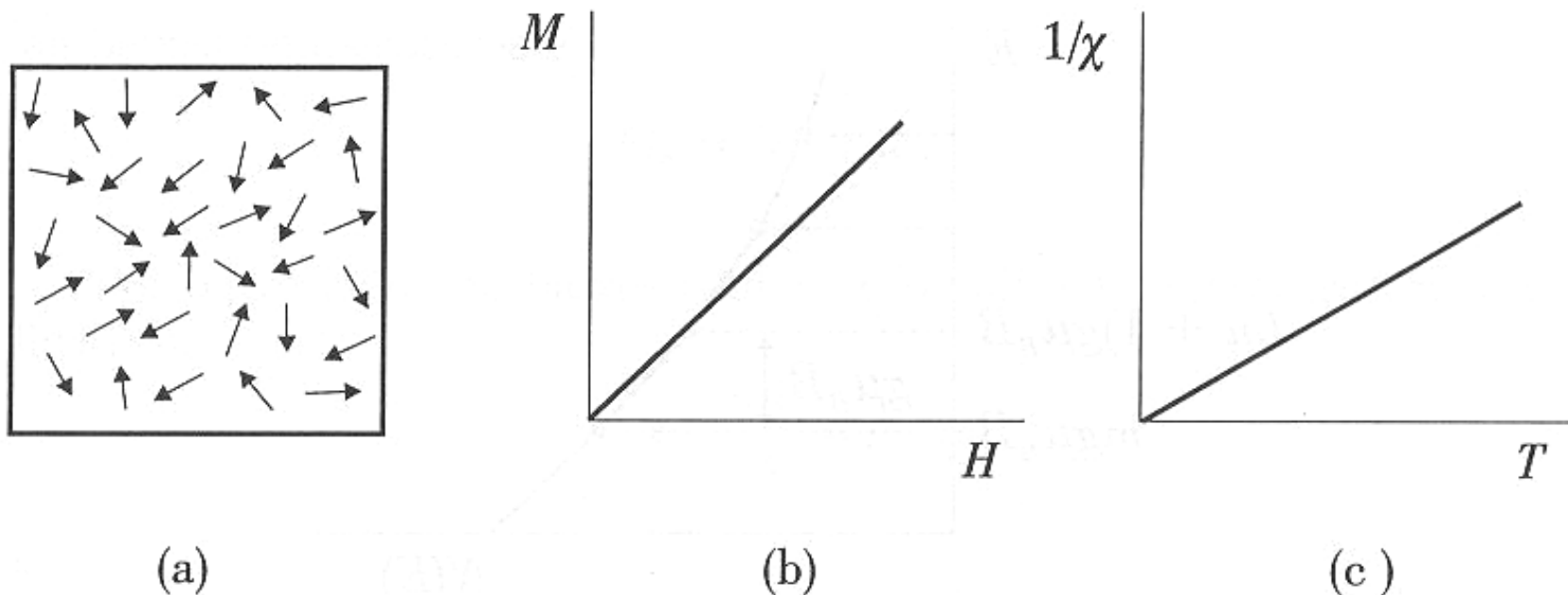
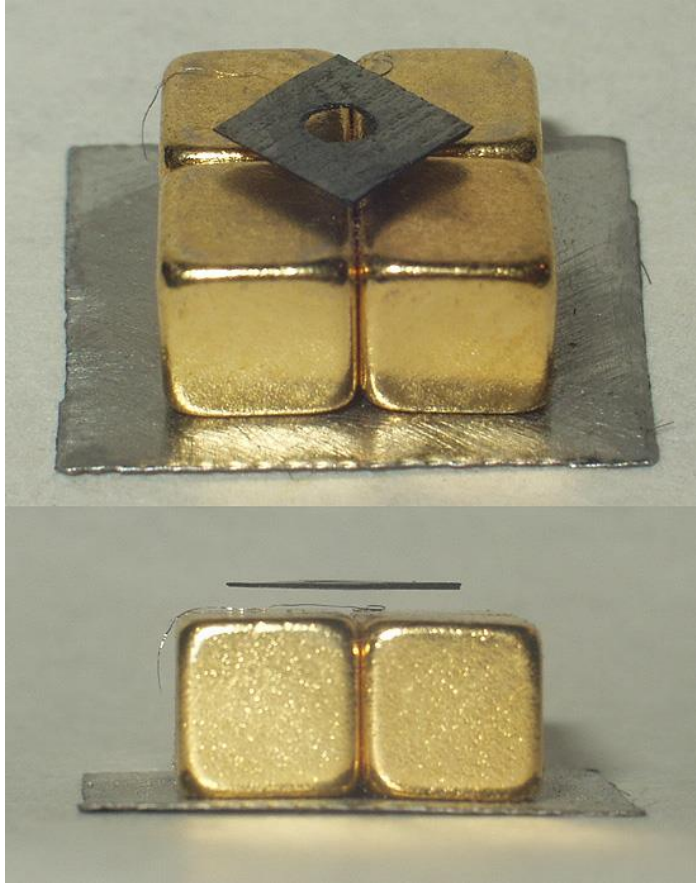
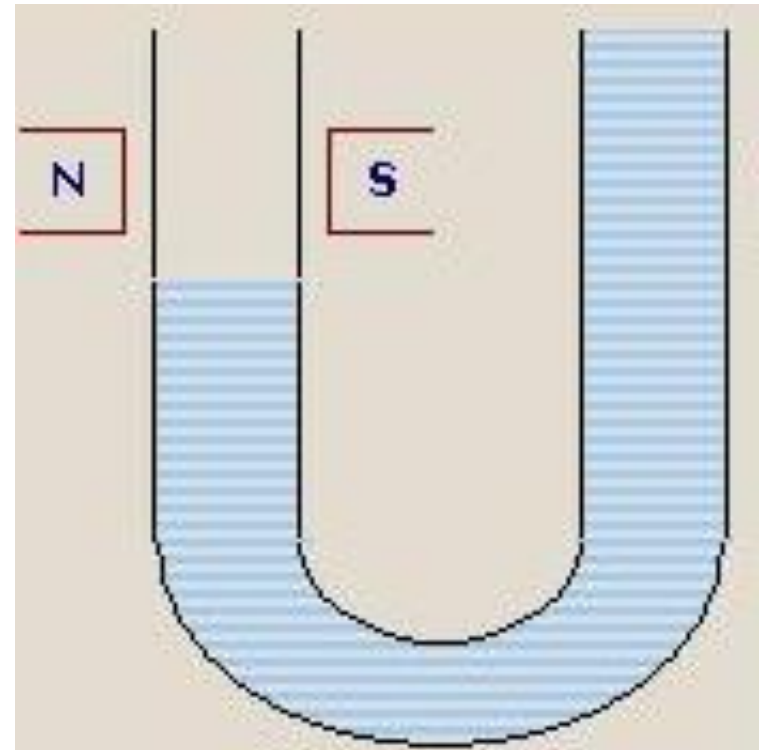


Figura 9.2: Características de materiais paramagnéticos: (a) Comportamento dos momentos magnéticos na ausência de campo externo; (b) Variação de  $M$  com  $H$  (a inclinação da curva é a susceptibilidade); (c) Variação do inverso da susceptibilidade com a temperatura.

# Diamagnetismo



**Grafite ou Carbono Pirolíticos**



**Água**

<https://www.youtube.com/watch?v=jyqOTJOJSou>

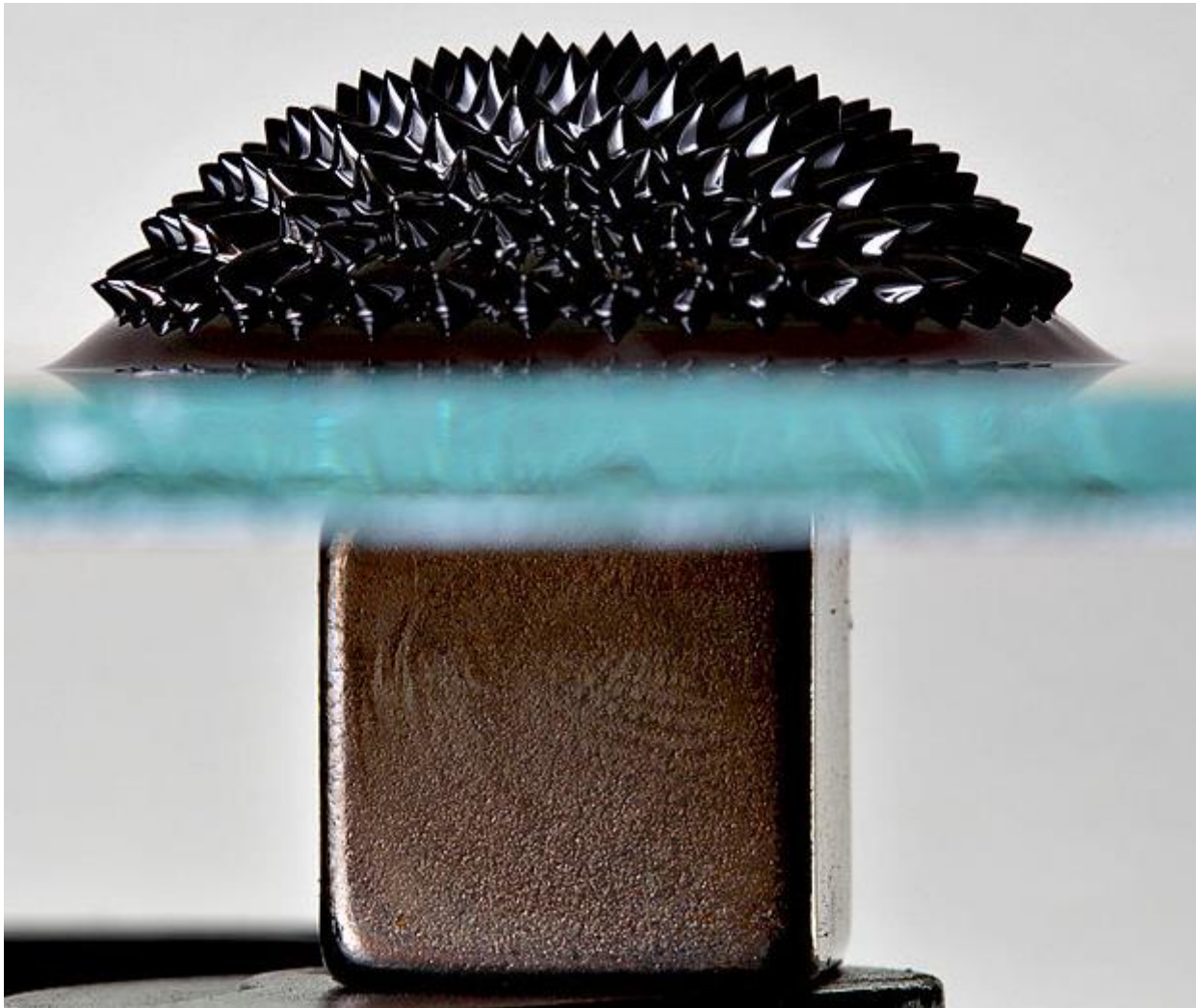
## Ferromagnetismo (Temperatura de Curie)

Material	$T_c$ K	$4\pi M(0)$ G	$4\pi M(300\text{ K})$ G
Fe	1043	22.016	21.450
Co	1394	18.171	17.593
Ni	631	6.409	6.095
Gd	293	24.881	0
CrBr <sub>3</sub>	37	3.393	0
EuO	77	24.002	0
EuS	16,5	14878	0

Tabela 9.2: Dados de alguns materiais ferromagnéticos no sistema CGS. Para obter o valor de  $\mu_0 M$  no SI basta multiplicar o valor de  $4\pi M$  por  $10^{-4}$ .



## Fluidos Ferromagnéticos (Ferrofluidos)





# Ferromagnetismo (Temperatura de Curie)

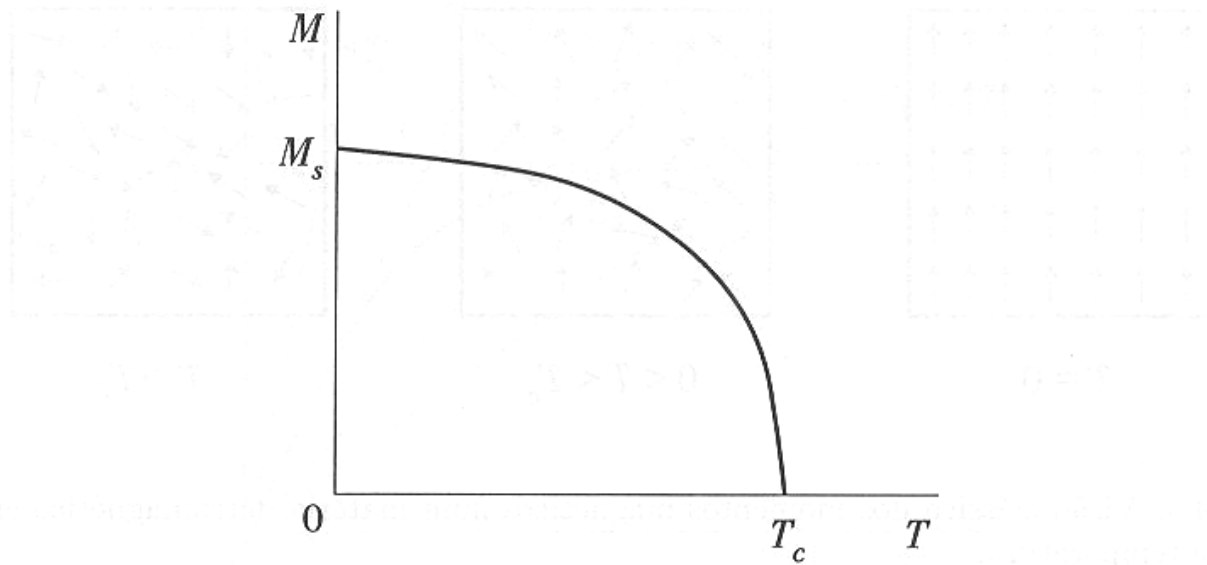


Figura 9.4: Variação da magnetização espontânea em materiais ferromagnéticos com a temperatura.

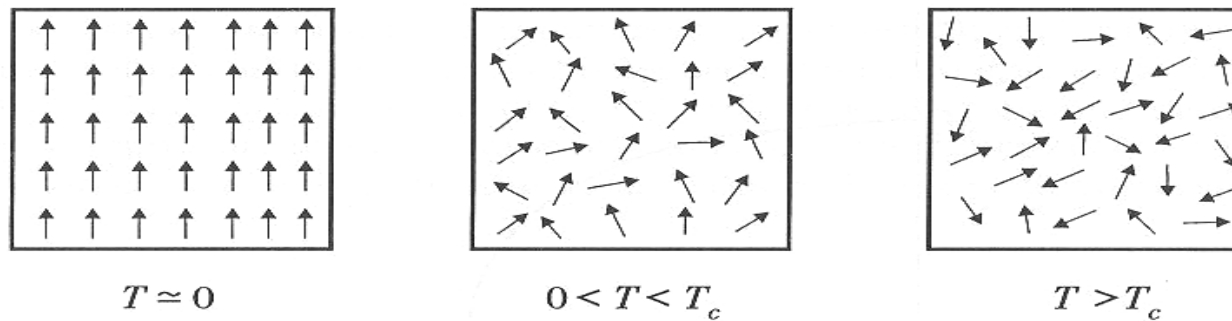
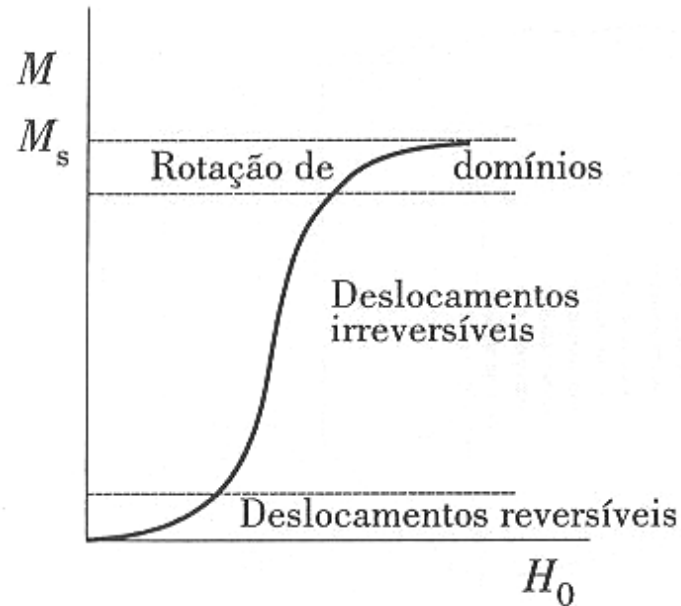
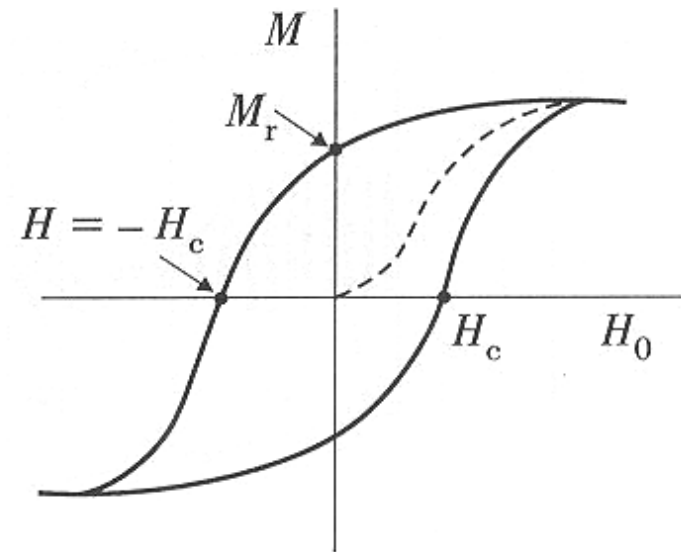


Figura 9.5: Visão clássica dos momentos magnéticos num material ferromagnético em três faixas de temperatura.

## Curva de Magnetização



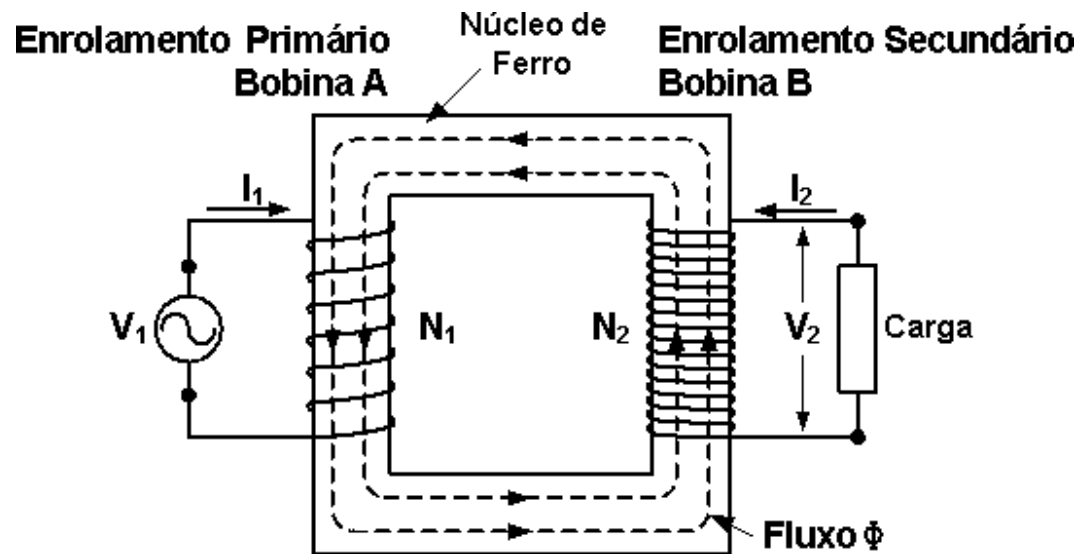
(a)



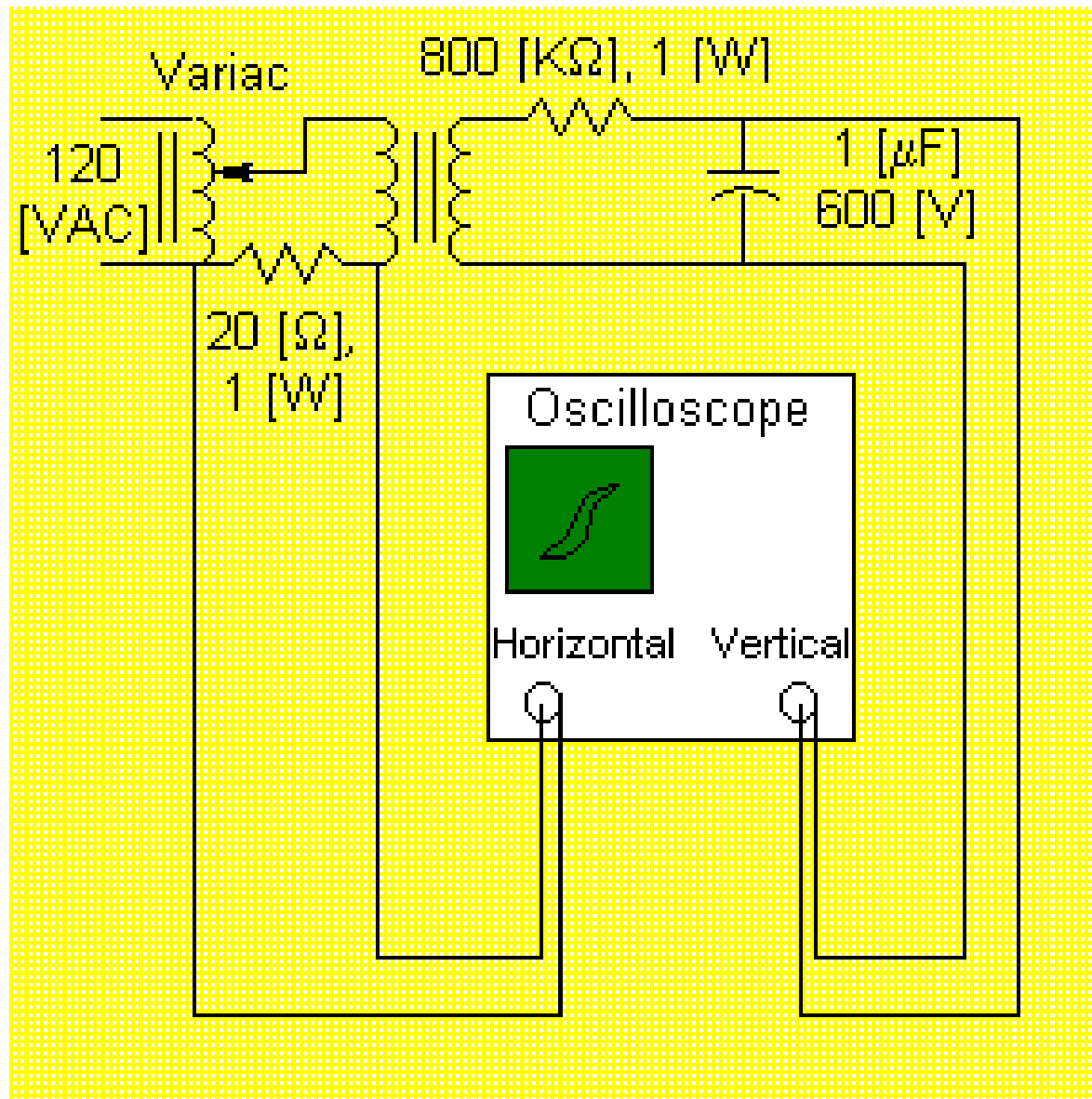
(b)

Figura 9.15: Variação da magnetização de material ferro ou ferrimagnético com o campo aplicado: (a) amostra inicialmente desmagnetizada; (b) curva de histerese.

# Transformadores



# Ensaio de Curva de Magnetização de um Transformador



## Curvas de Magnetização

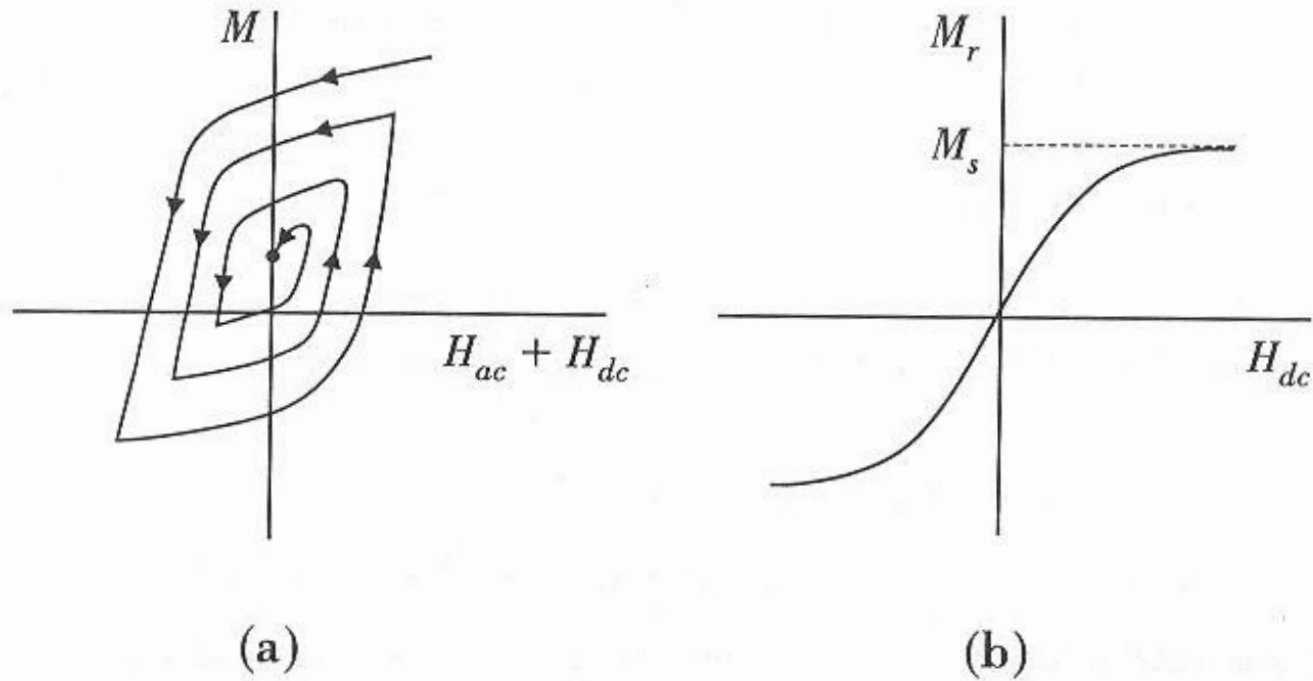


Figura 9.17: Processo de magnetização  $dc$  com polarização  $ac$ : (a) Trajetória de  $M$  no plano  $M-H$ ; (b) Curva de magnetização remanente em função de  $H_{dc}$ , na qual não existe o ciclo de histerese.

## Curvas de Desmagnetização

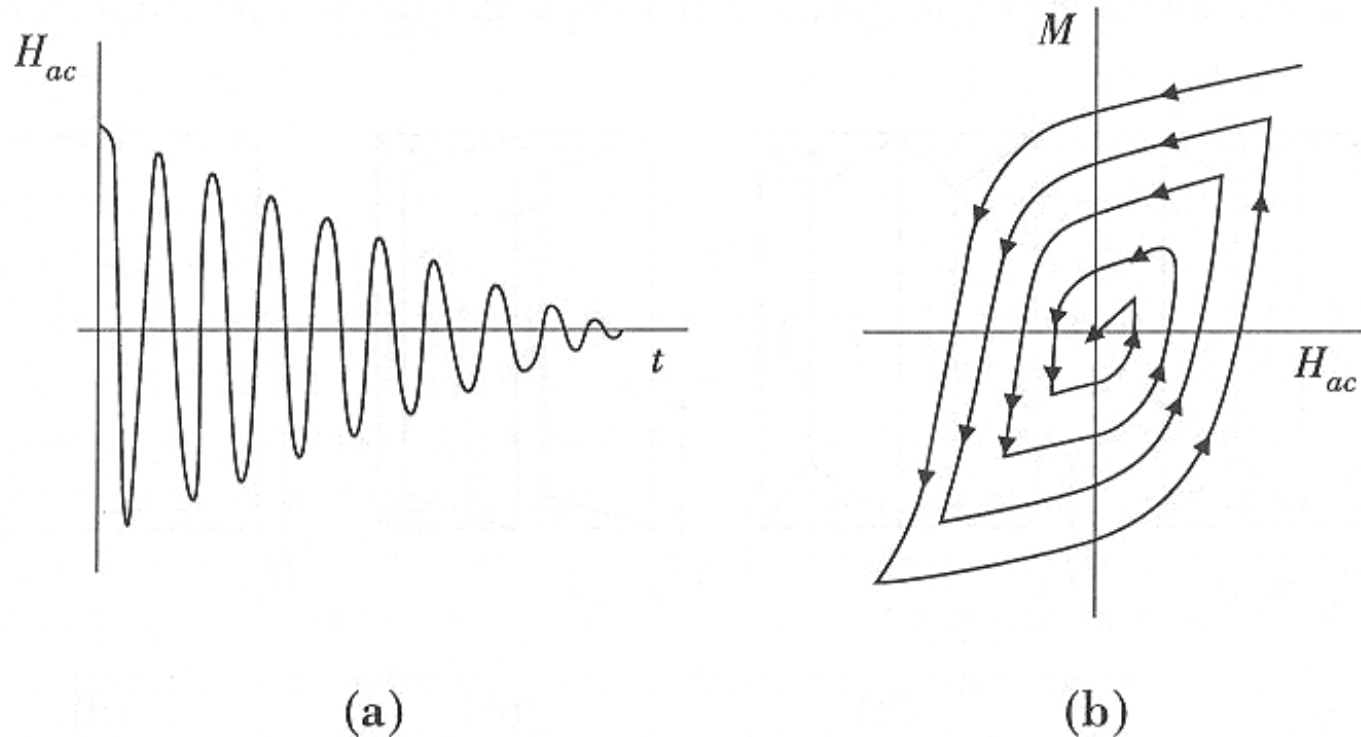
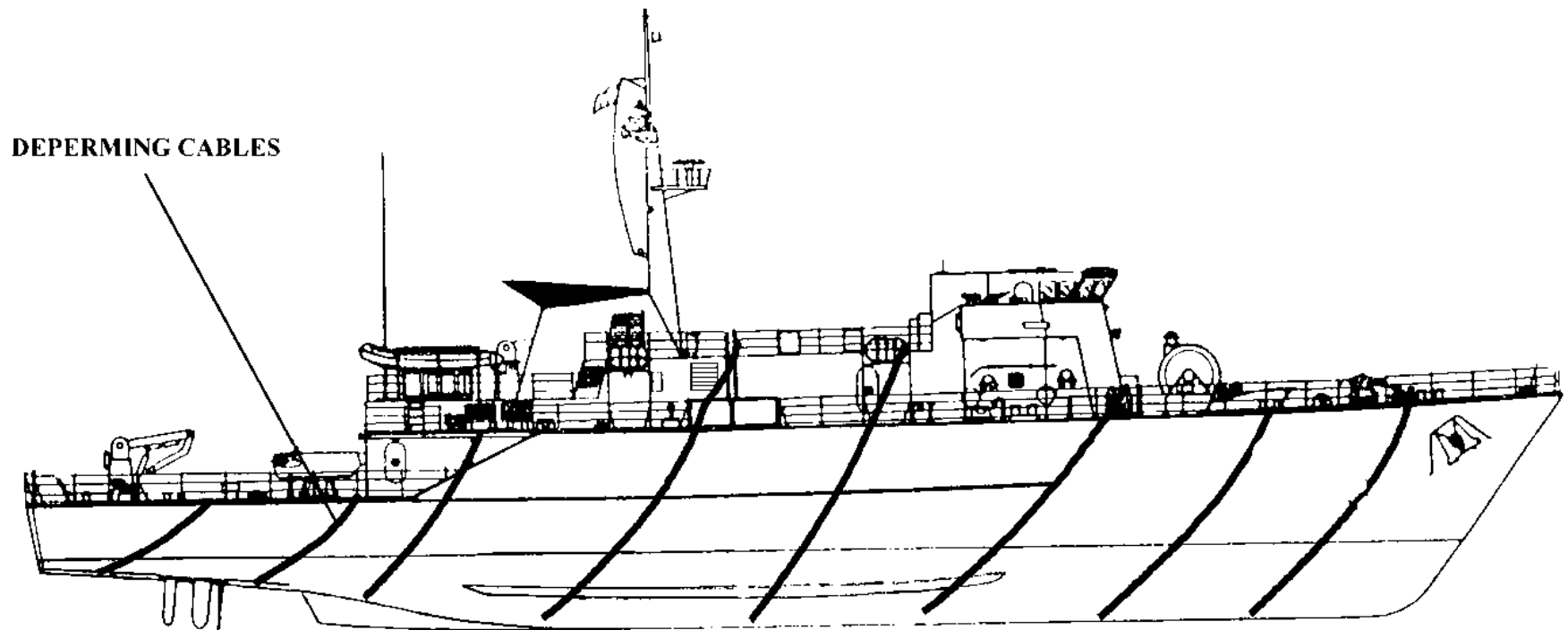


Figura 9.16: Processo de desmagnetização *ac* de um material ferromagnético: (a) Campo  $H$  alternado com amplitude decrescente; (b) Trajetória de  $M$  no plano  $M - H$ .

## Desmagnetização de Grandes Navios (Degaussing ou Deperming)





## Apagador de Hard Disks



## Curvas de Magnetização

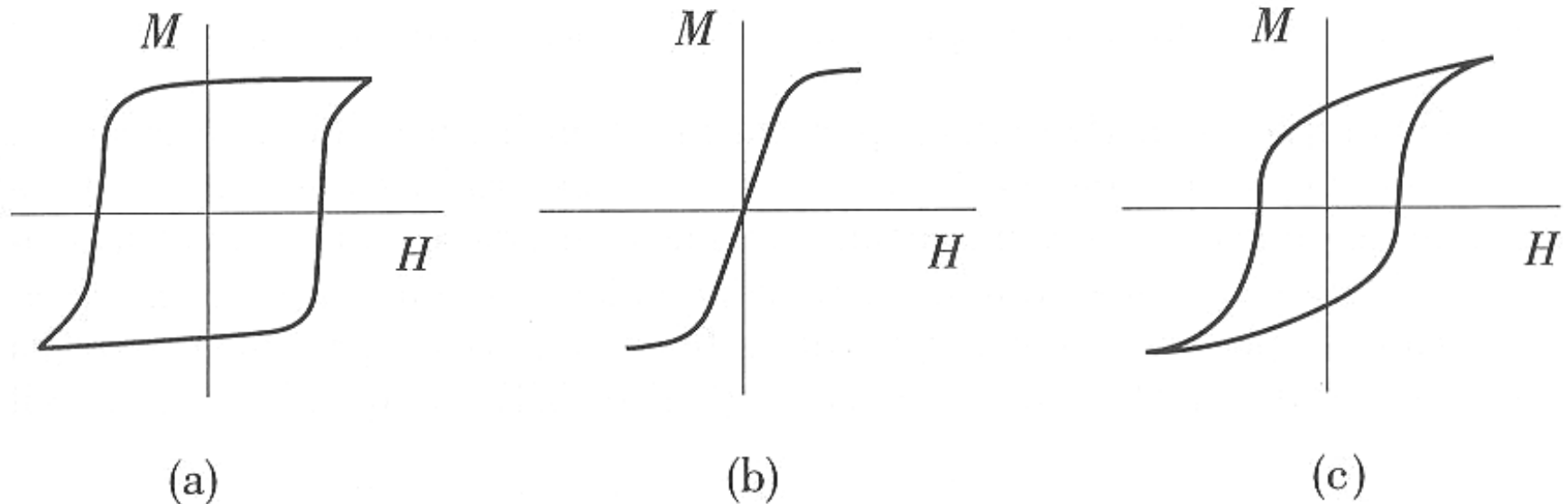
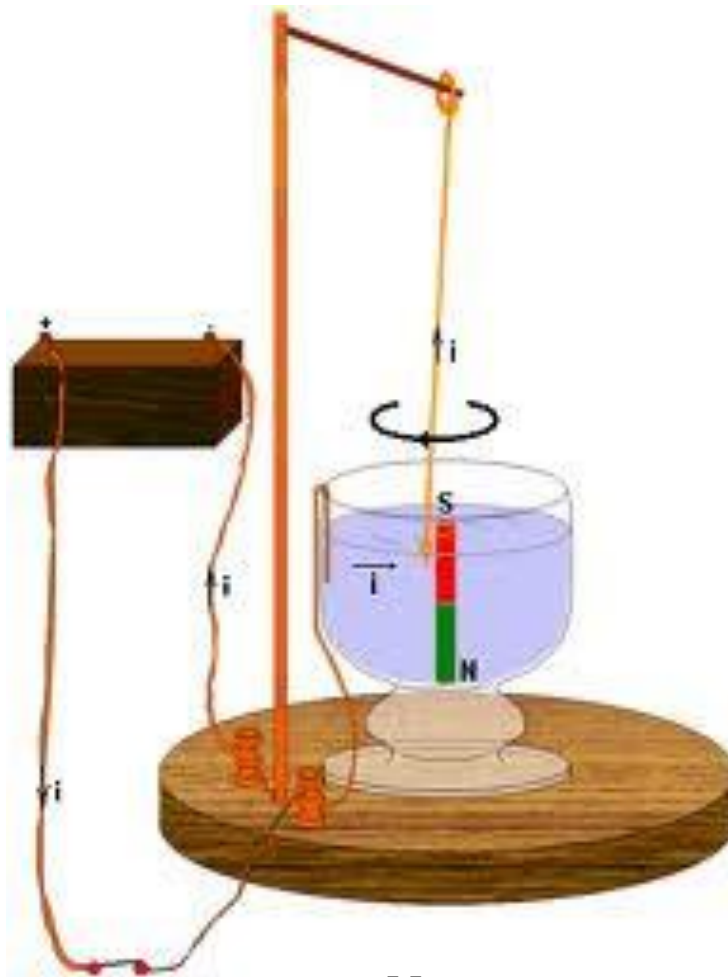


Figura 9.18: Ciclos de histereses de materiais magnéticos: (a) Materiais duros, ou ímãs permanentes; (b) Materiais moles, ou permeáveis; (c) Materiais intermediários para gravação magnética.

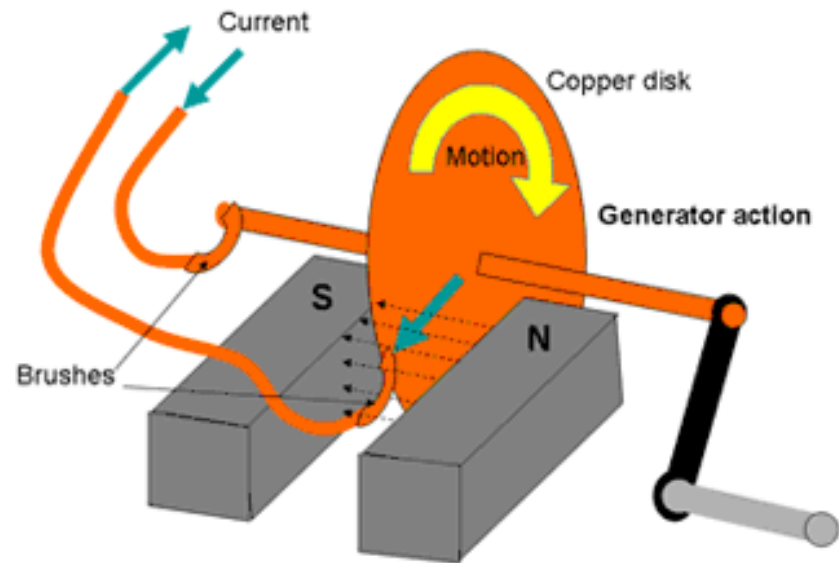
# Motores e Geradores Elétricos



Michael Faraday



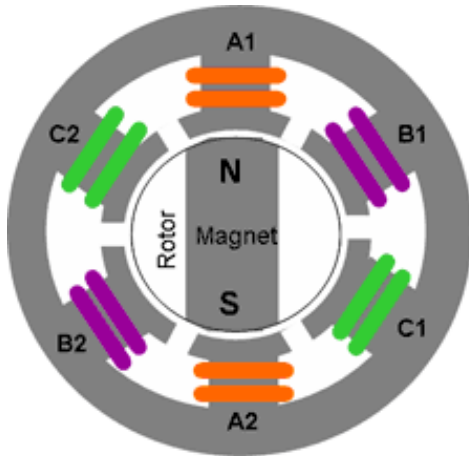
**Motor  
(1821)**



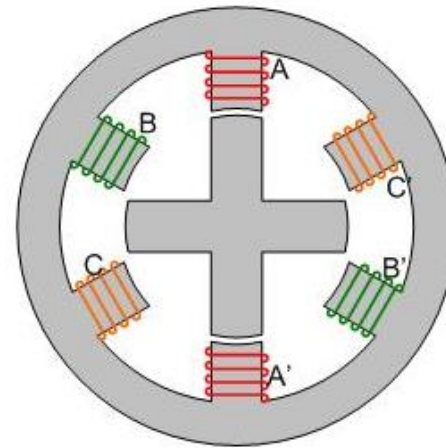
**Dínamo  
(1831)**

# Motores / Geradores Elétricos

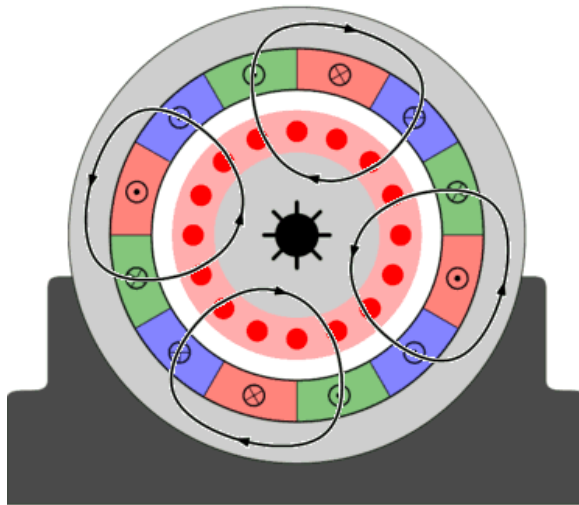
## Conversão Eletromecânica de Energia



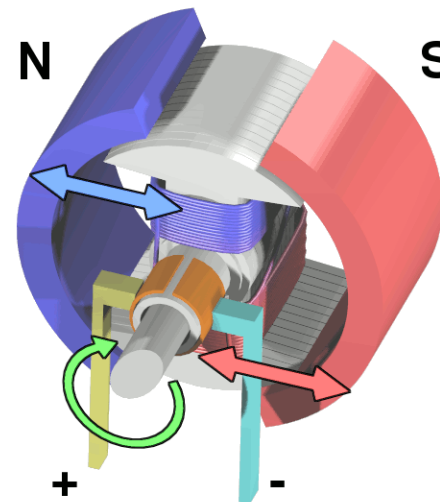
**Motor DC sem Escovas**



**Motor de Relutância Chaveado**



**Motor de Indução 3Φ**



**Motor DC**

# Motor de Indução 3 $\Phi$

