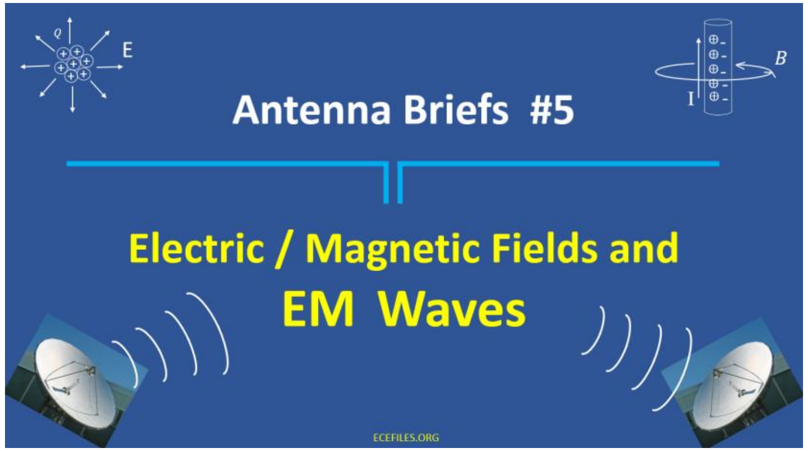
Antenna Briefs #5 -- Electric Fields, Magnetic Fields, and EM Waves

Companion video at: https://www.youtube.com/watch?v=6C-IETDAY1s

Episode 5 focuses on the electric, magnetic, and electromagnetic fields produced by antennas. We also provide some key engineering results here. For example: How does one find the field strength in volts/meter produced by an antenna and how do we map that to the voltage that a receiving antenna produces? How can we build transmitters that obey regulatory rules? A brief preview of the next episode is also provided, where we ask the questions: what is a B field (spoiler: it's really just an E field in another relativistic frame of reference), and how do we calculate and simulate far-field patterns from antennas...



Antenna Briefs #5

Electric / Magnetic Fields and EM Waves

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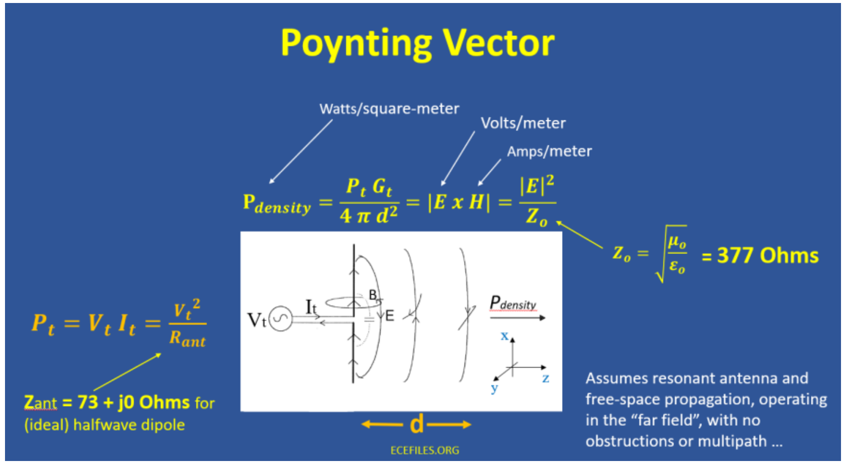

Poynting Vector

$$P_{density} = \frac{P_t\, G_t}{4\,\pi\, d^2} = |E \times H| = \frac{|E|^2}{Z_o}$$

Watts/square-meter

Volts/meter

Amps/meter

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 377 \text{ Ohms}$$

$$P_t = V_t\, I_t = \frac{{V_t}^2}{R_{ant}}$$

Zant = 73 + j0 Ohms for (ideal) halfwave dipole

Assumes resonant antenna and free-space propagation, operating in the "far field", with no obstructions or multipath ...

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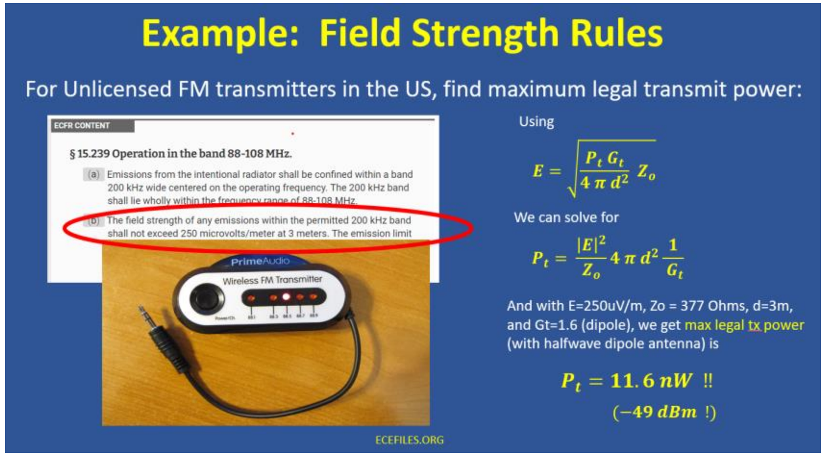

Example: Field Strength Rules

For Unlicensed FM transmitters in the US, find maximum legal transmit power:

ECFR CONTENT

§ 15.239 Operation in the band 88-108 MHz.

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(b) The field strength of any emissions within the permitted 200 kHz band shall not exceed 250 microvolts/meter at 3 meters. The emission limit

Using

$$E = \sqrt{\frac{P_t\, G_t}{4\,\pi\, d^2}\, Z_o}$$

We can solve for

$$P_t = \frac{|E|^2}{Z_o} 4\,\pi\, d^2 \frac{1}{G_t}$$

And with E=250uV/m, Zo = 377 Ohms, d=3m, and Gt=1.6 (dipole), we get max legal tx power (with halfwave dipole antenna) is

$$P_t = 11.6\, nW \;!!$$

$$(-49\, dBm\; !)$$

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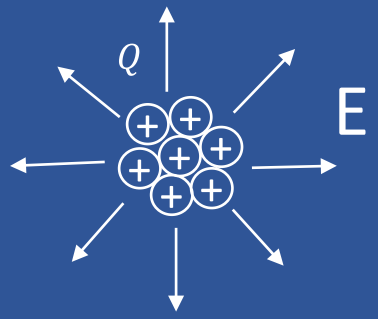

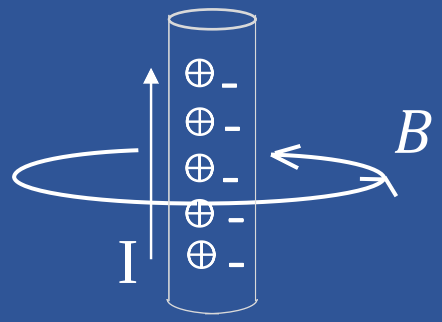

Antenna Briefs #5

Electric / Magnetic Fields and EM Waves

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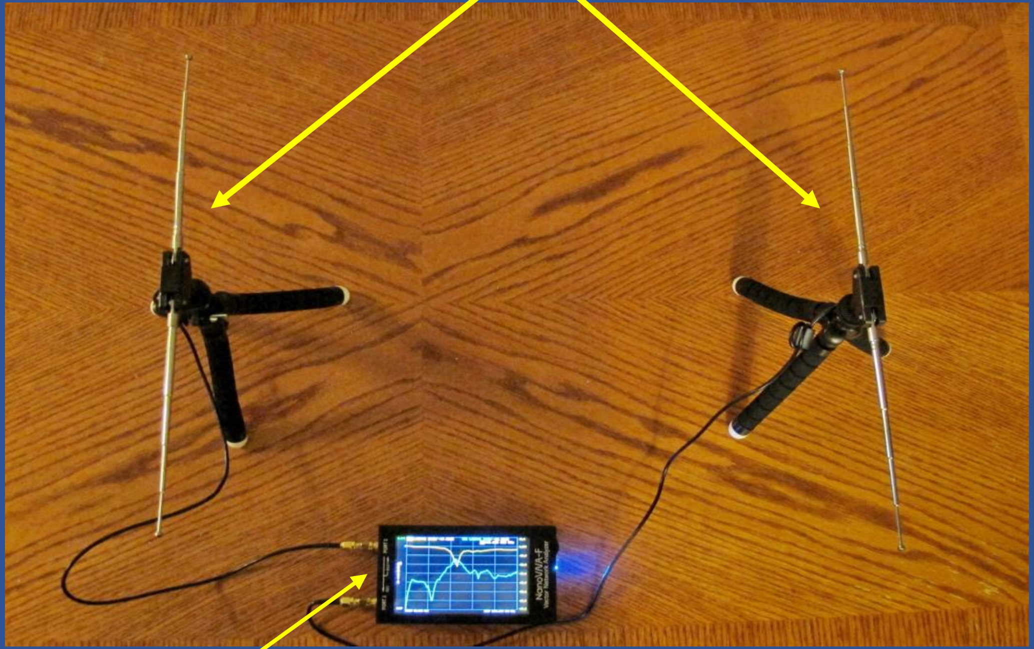
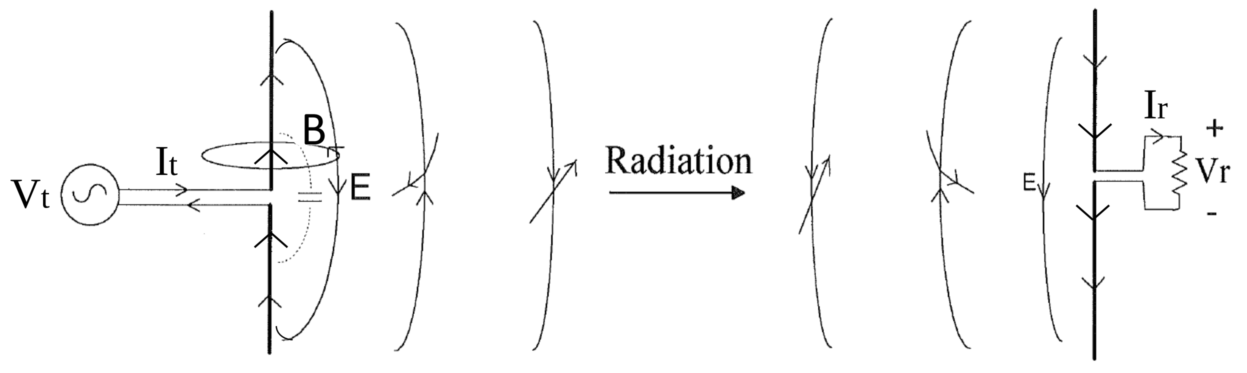
EM Waves in Free Space

Dipole Antennas



NanoVNA

(Transmitter, receiver, display)

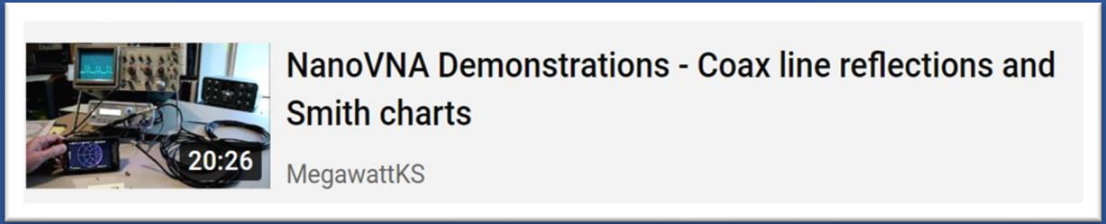


Voltage Source sets
up currents in tx antenna

Currents Launch
E and B Fields

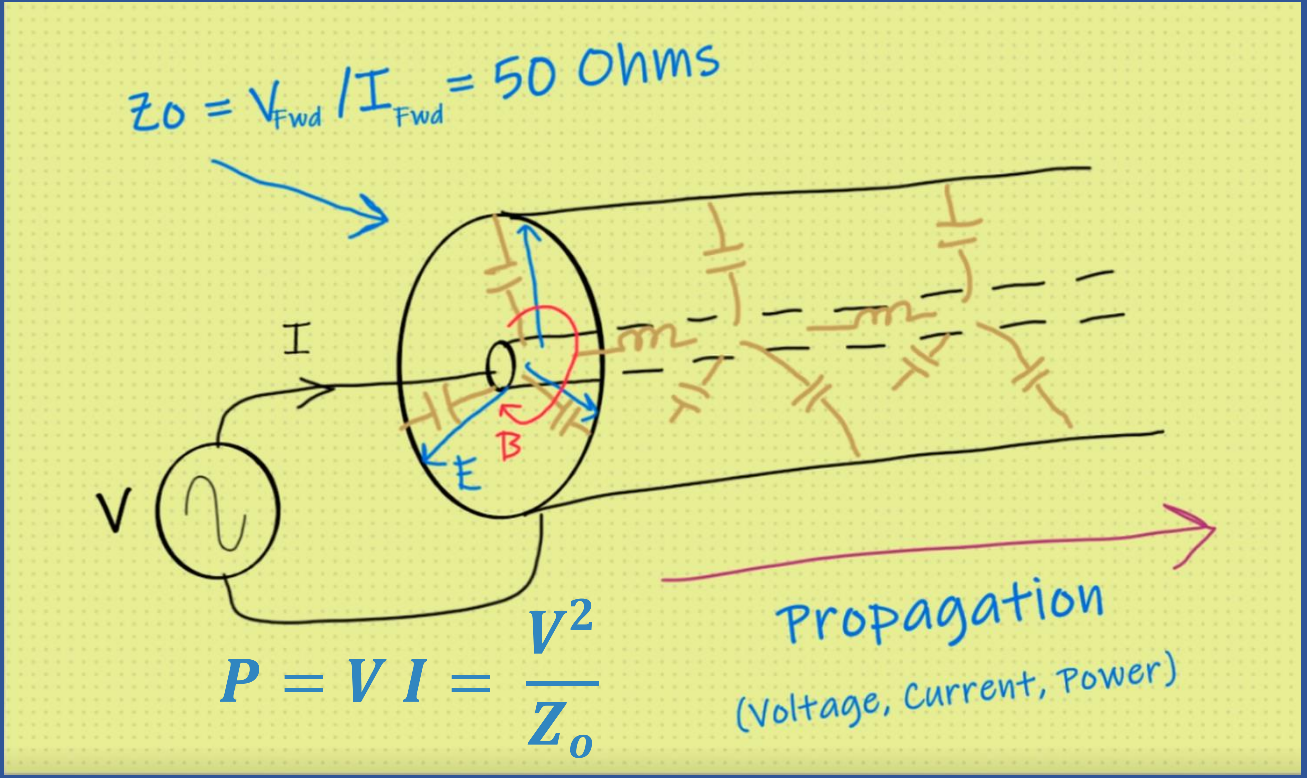
Fields induce
voltage/current
in rx antenna

Guided EM Waves in Coax



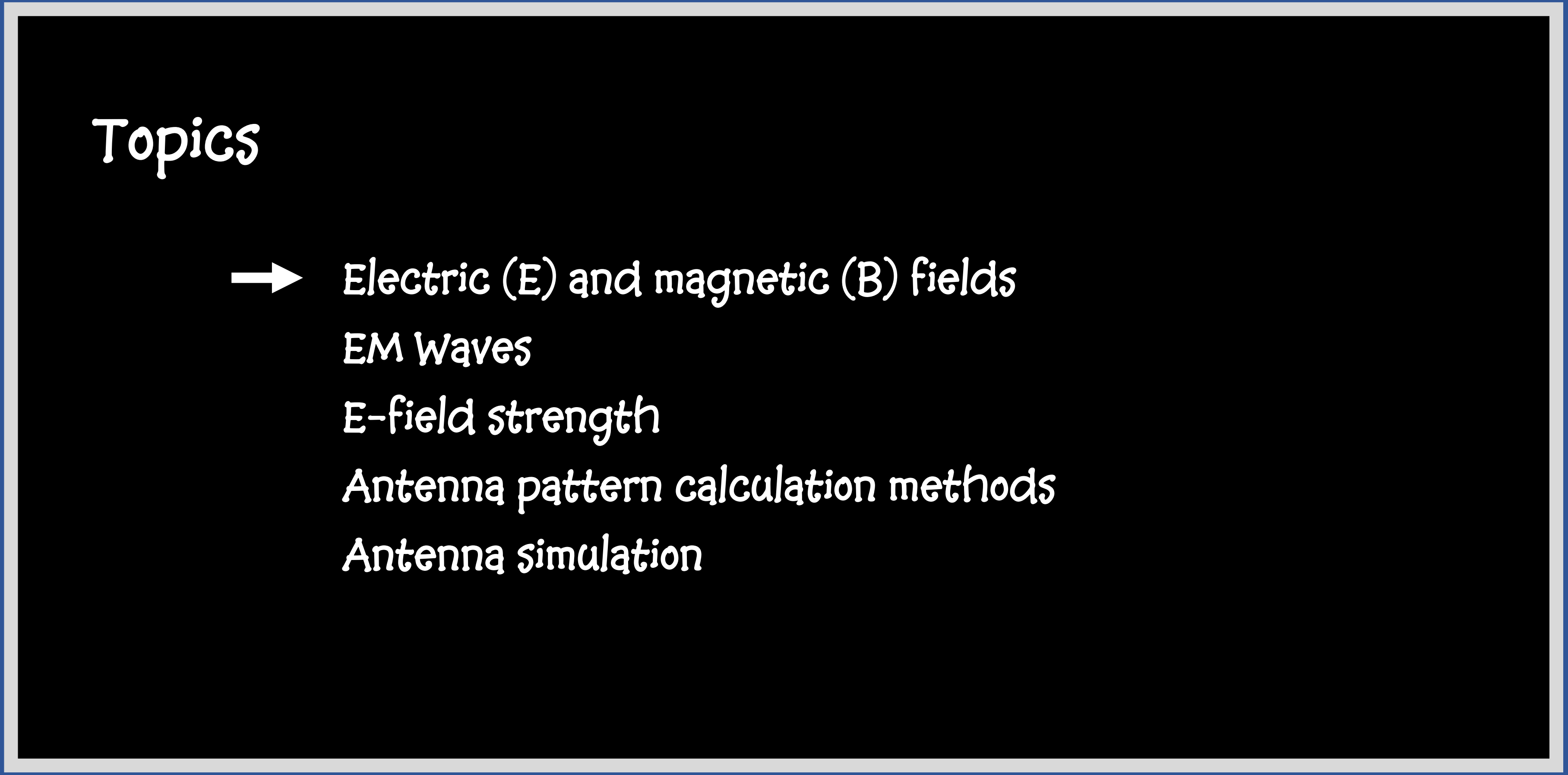
NanoVNA Demonstrations - Coax line reflections and Smith charts

MegawattKS



$$P = V\,I = \frac{V^2}{Z_o}$$

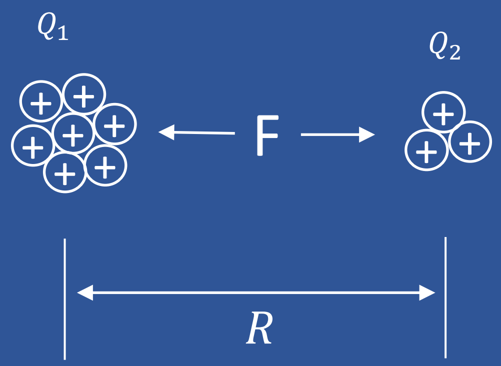
Topics



Topics

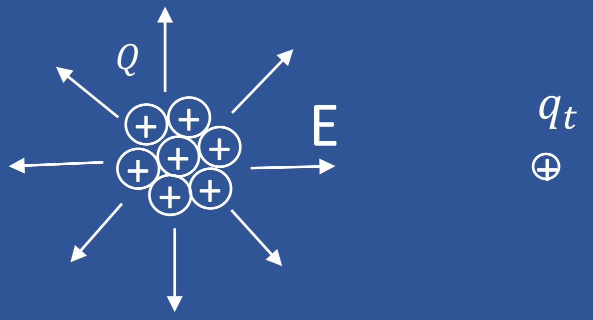
→ Electric (E) and magnetic (B) fields
EM Waves
E-field strength
Antenna pattern calculation methods
Antenna simulation

Electric Field: E



$$F = \frac{Q_1\, Q_2}{4\, \pi\, \varepsilon_o\, R^2}$$

Coulomb's law



$$\boldsymbol{E} \triangleq \frac{\boldsymbol{F}}{q_t}$$

E field definition

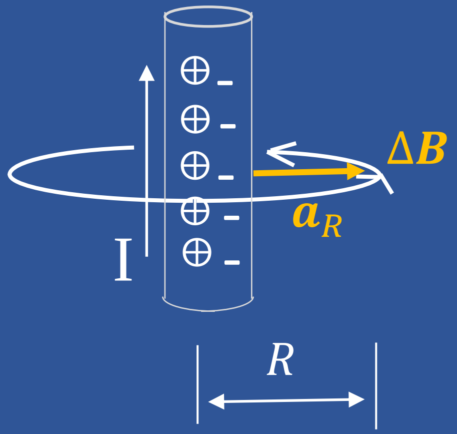
Volts/meter

ε_o= 8.854E-12 F/m Permittivity (of free-space)

Magnetic Field: B

$$\Delta \boldsymbol{B} = \mu_o \frac{I\ \Delta \boldsymbol{L}\ x\ \boldsymbol{a}_R}{4\ \pi\ \ R^2}$$

Biot Savart law



Close to wire, we get:

$$B\ = \mu_o \frac{I}{2\ \pi\ R} = \mu_o H$$

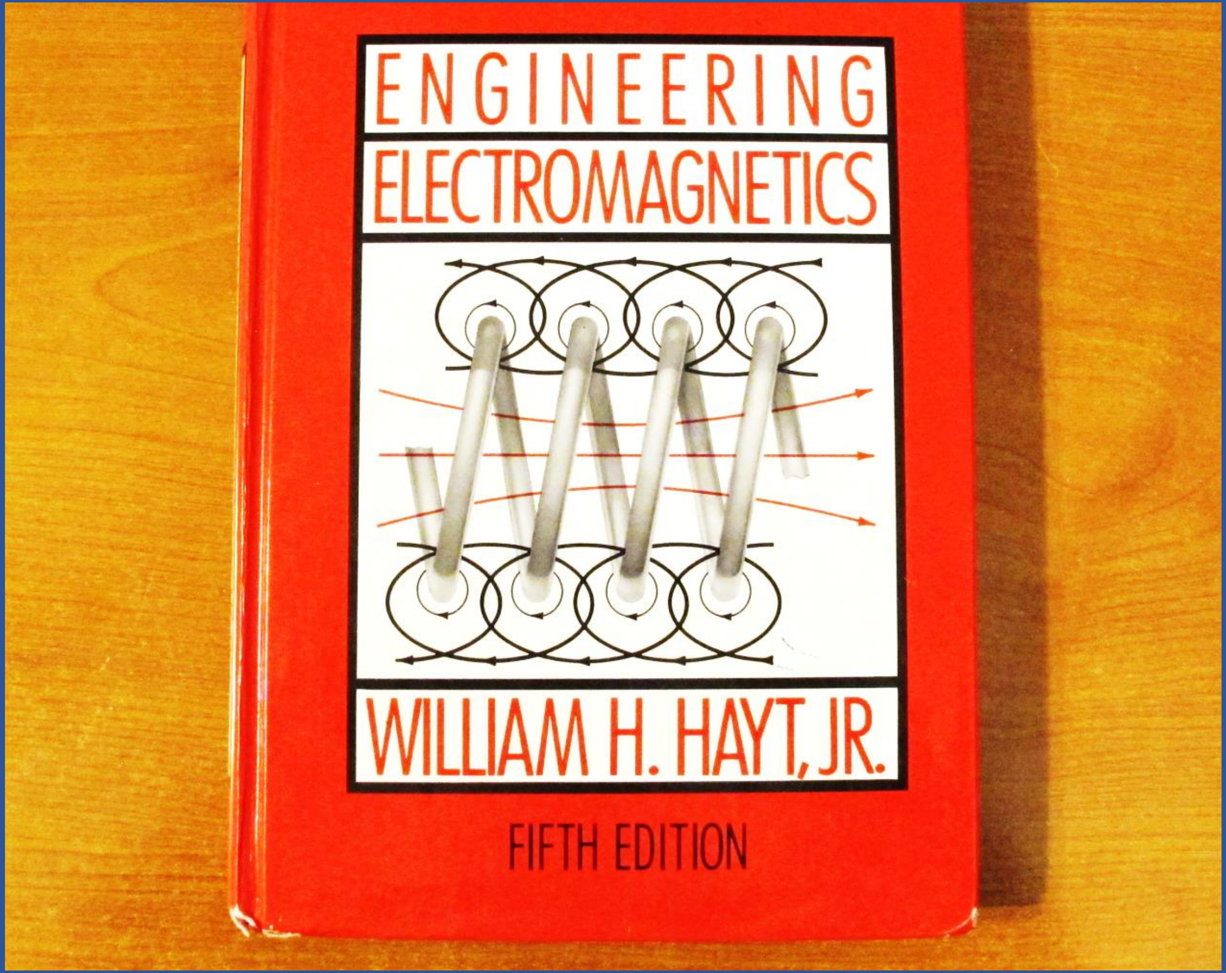
Ampere’s law

Amps/meter

$$\underline{\boldsymbol{\mu_o} = \mathbf{1.257\ E - 6\ \ H/m}}$$

Permeability
(of free-space)

A Good EM Textbook



Fifth Edition

4.5/5 stars

Out of print ☹

Topics

Topics

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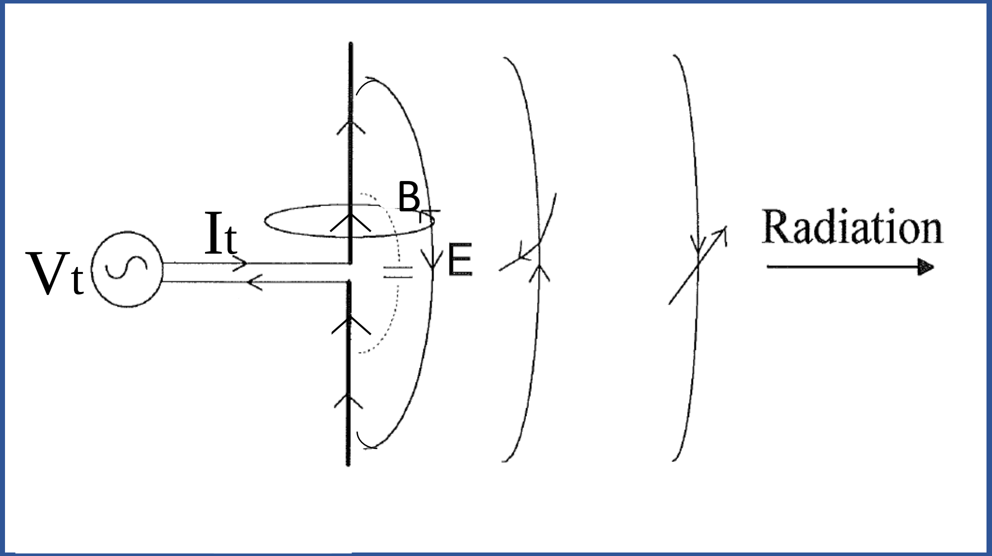
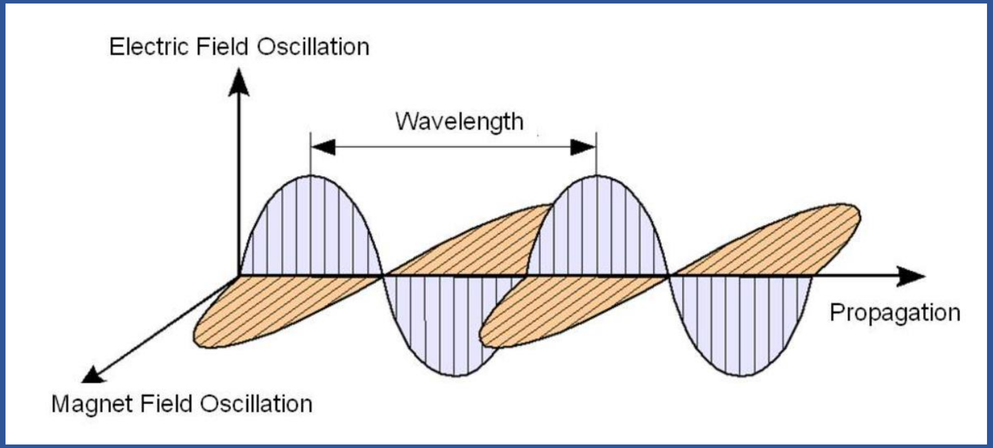
- → EM Waves
- E-field strength
- Antenna pattern calculation methods
- Antenna simulation

Electro-magnetic Fields



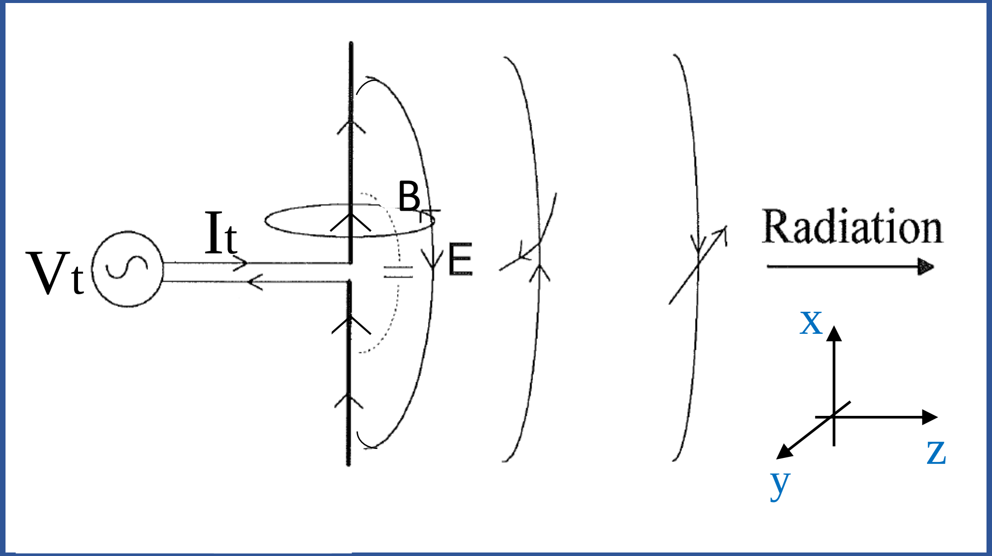


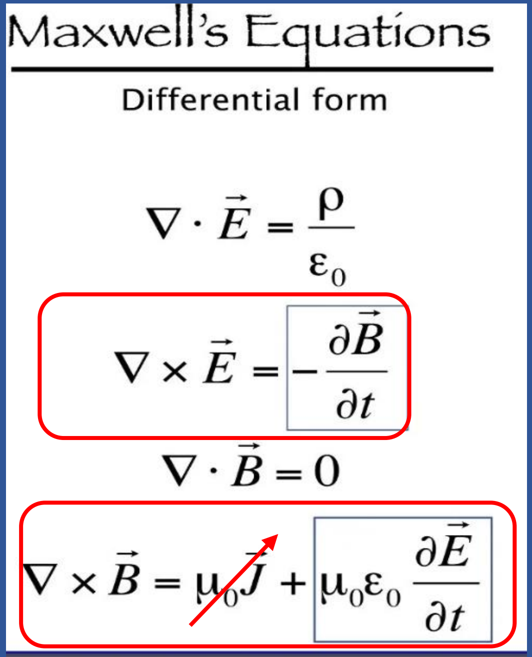
From: http://cleanenergywiki.org/index.php?title=File:Emwavepropagation.jpg

NOTE: Illustrations are Snapshots in Time

EM Fields are sinewaves in space and time, and move to right with velocity c (speed of light)

Plane-wave Solutions in Free-Space





Maxwell's Equations

Differential form

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\boxed{\nabla \times \vec{E} = \boxed{-\frac{\partial \vec{B}}{\partial t}}}$$

$$\nabla \cdot \vec{B} = 0$$

$$\boxed{\nabla \times \vec{B} = \cancel{\mu_0 \vec{J}} + \boxed{\mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}}}$$

From: https://owlcation.com/stem/maxwell-equations-displacement-current

Far from (and broadside to) antenna, Maxwell's equations simplify to:

$$\frac{\Delta E_x}{\Delta z} = -\frac{\Delta B_y}{\Delta t}$$

$$-\frac{\Delta B_y}{\Delta z} = \mu_o \varepsilon_o \frac{\Delta E_x}{\Delta t}$$

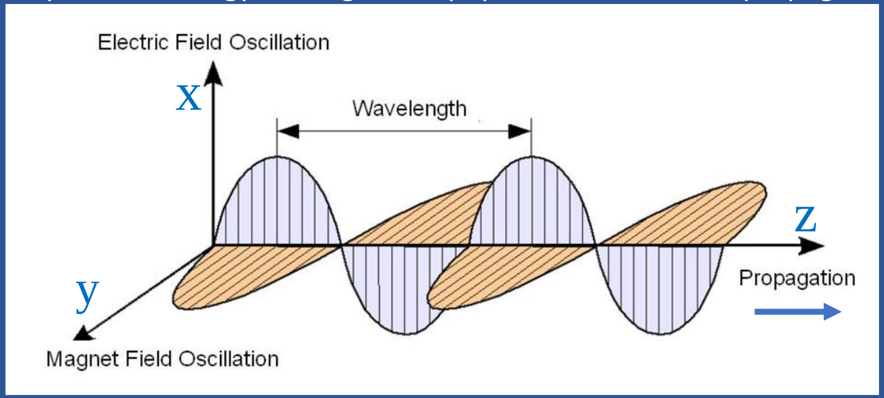
Which has solutions:

$$E_x = E_o \cos\left(2\pi f\left(t - \frac{z}{c}\right)\right) \quad \text{and} \quad B_y = \frac{1}{c} E_x$$

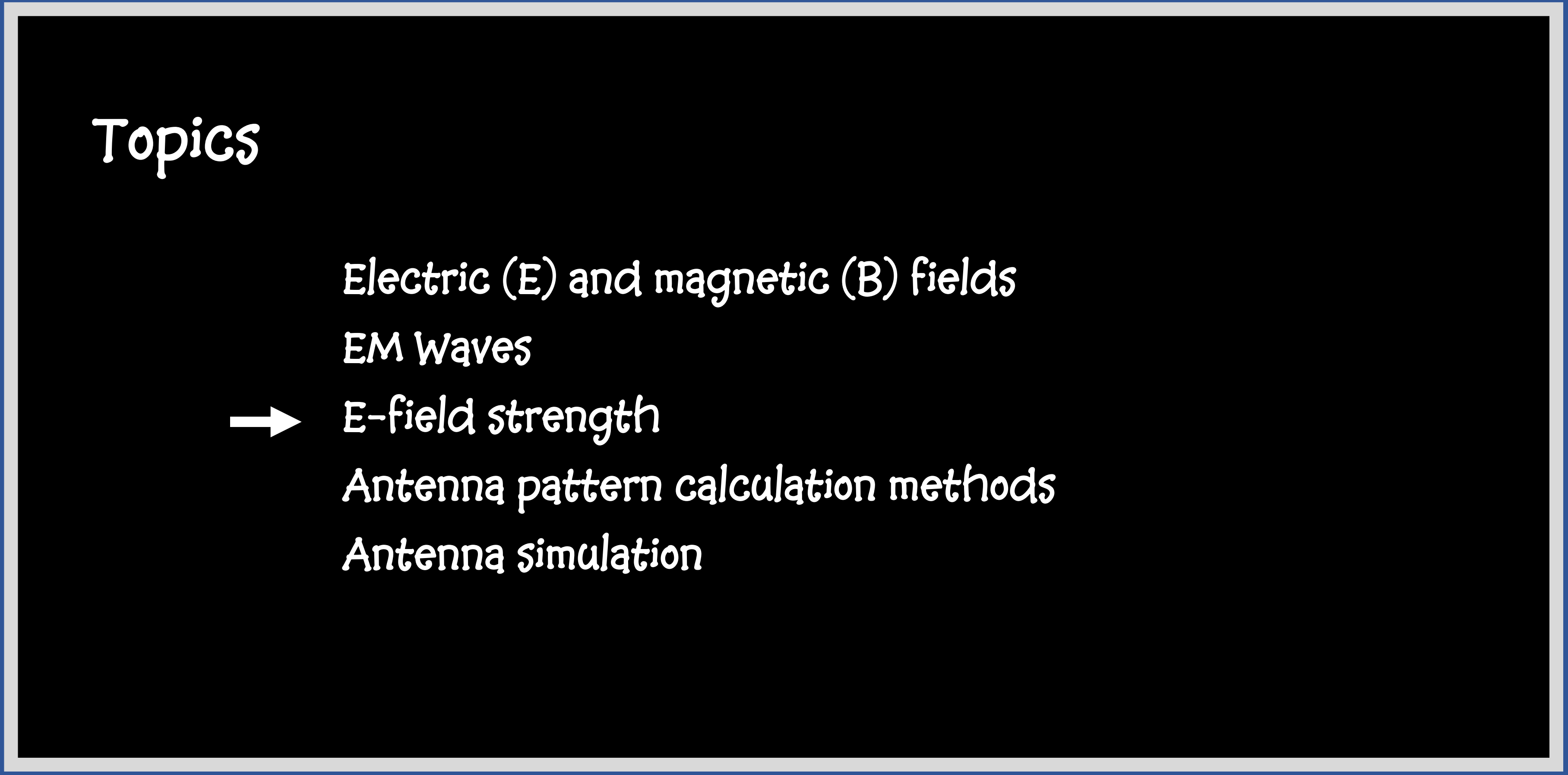
?

With $c = \sqrt{\frac{1}{\mu_o \varepsilon_o}} = 2.998E8$ meters/second

From: http://cleanenergywiki.org/index.php?title=File:Emwavepropagation.jpg



Topics



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- EM Waves
- → E-field strength
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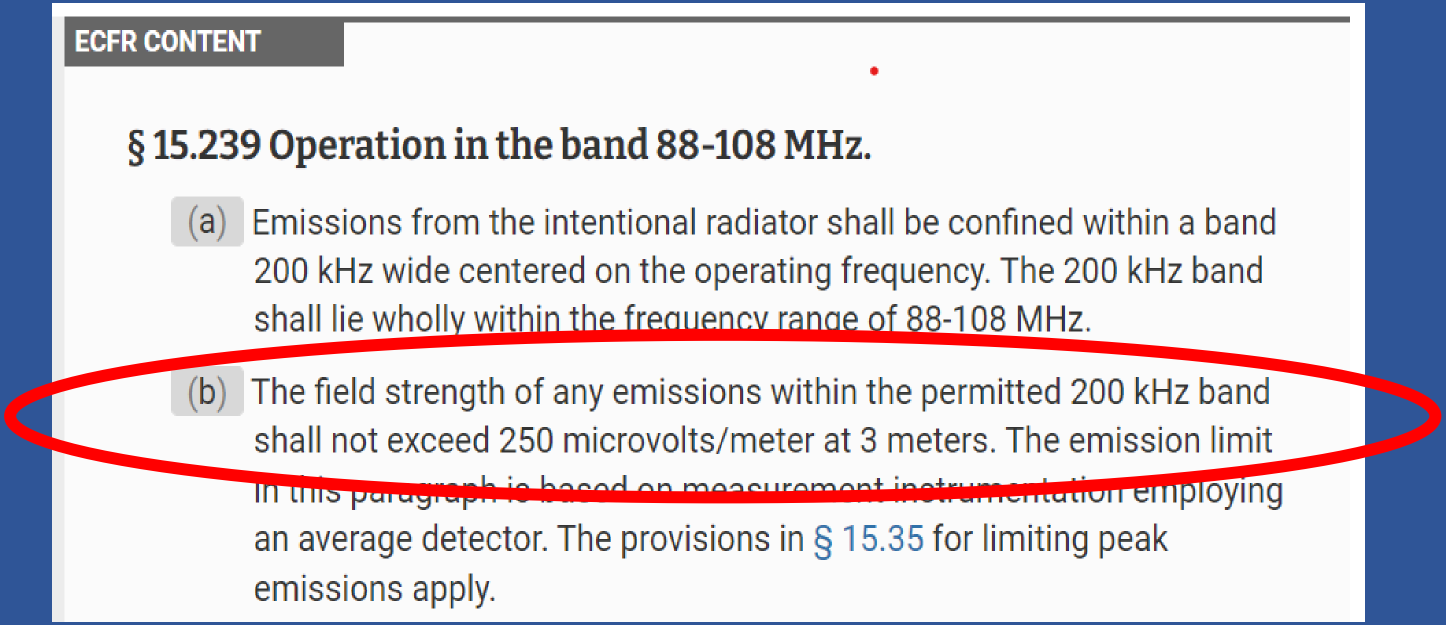
Example 1: Field Strength Rules

Find maximum legal transmit power for unlicensed FM transmitters



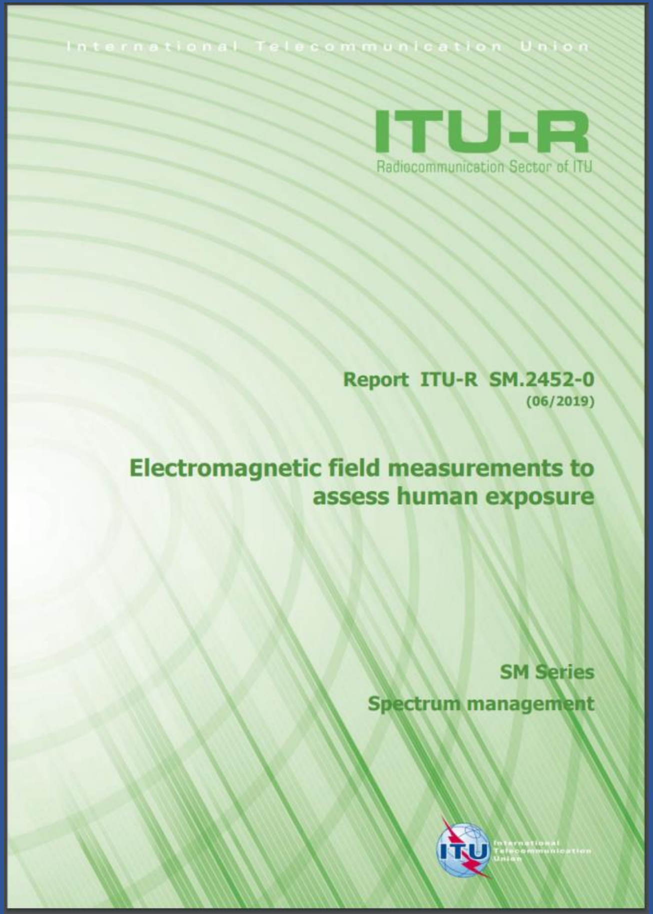
ECFR CONTENT

§ 15.239 Operation in the band 88-108 MHz.

(a) Emissions from the intentional radiator shall be confined within a band 200 kHz wide centered on the operating frequency. The 200 kHz band shall lie wholly within the frequency range of 88-108 MHz.

(b) The field strength of any emissions within the permitted 200 kHz band shall not exceed 250 microvolts/meter at 3 meters. The emission limit in this paragraph is based on measurement instrumentation employing an average detector. The provisions in § 15.35 for limiting peak emissions apply.

Example 2: E-Field Exposure Limits



International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Report ITU-R SM.2452-0

(06/2019)

Electromagnetic field measurements to assess human exposure

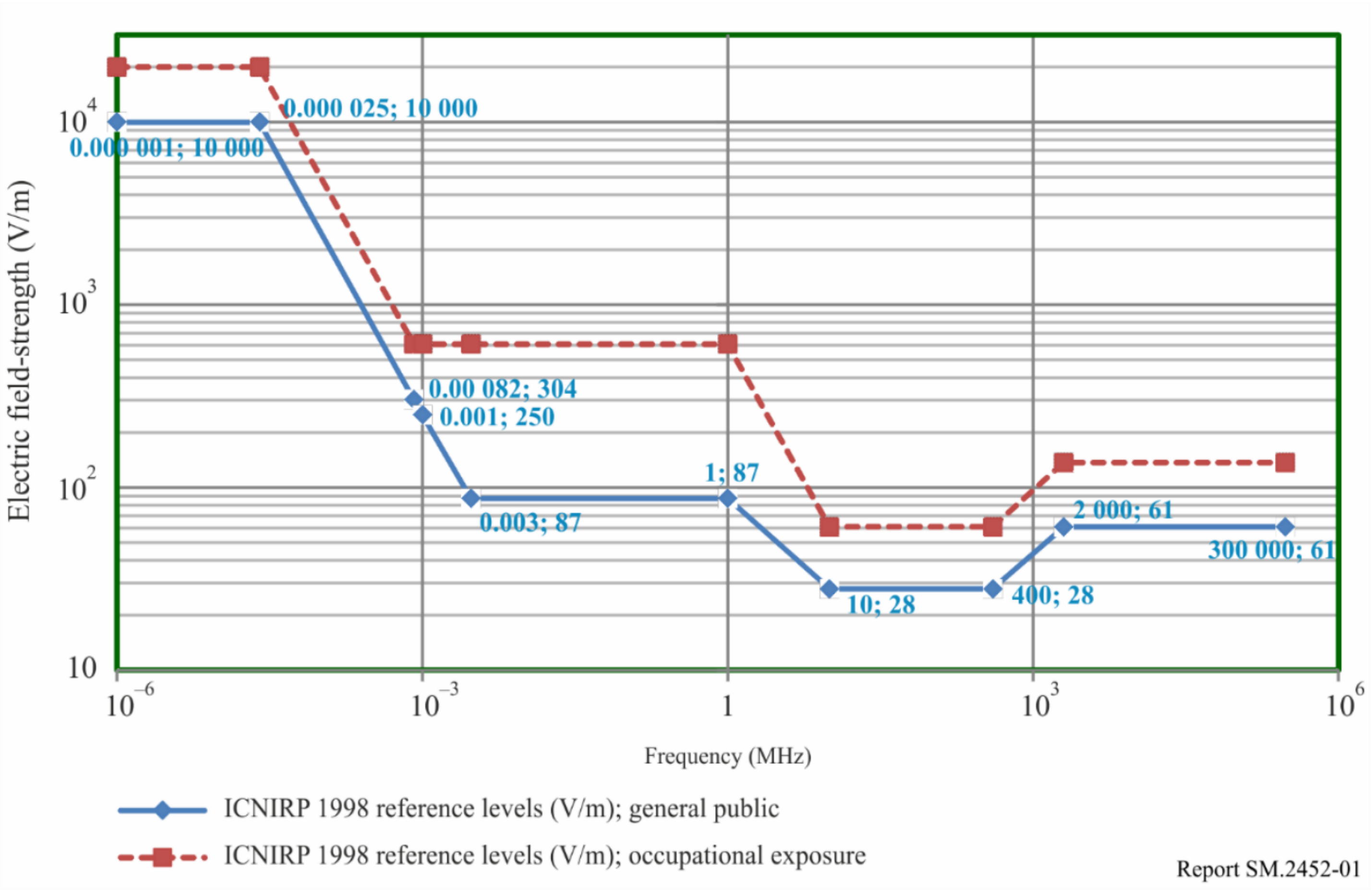
SM Series

Spectrum management

https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-SM.2452-2019-PDF-E.pdf

FIGURE 1[3]

ICNIRP 1998 electric field-strength for occupational and general public exposure



Report SM.2452-01

Poynting Vector

Watts/square-meter

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Amps/meter

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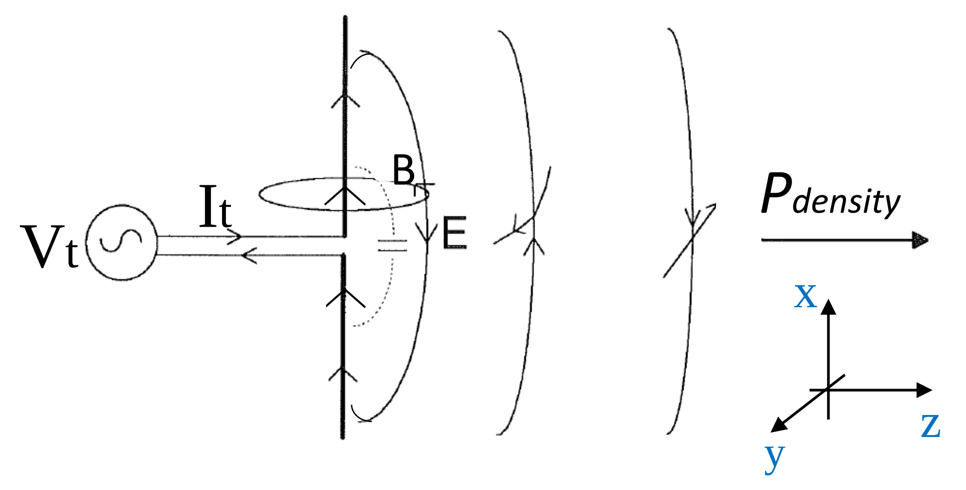

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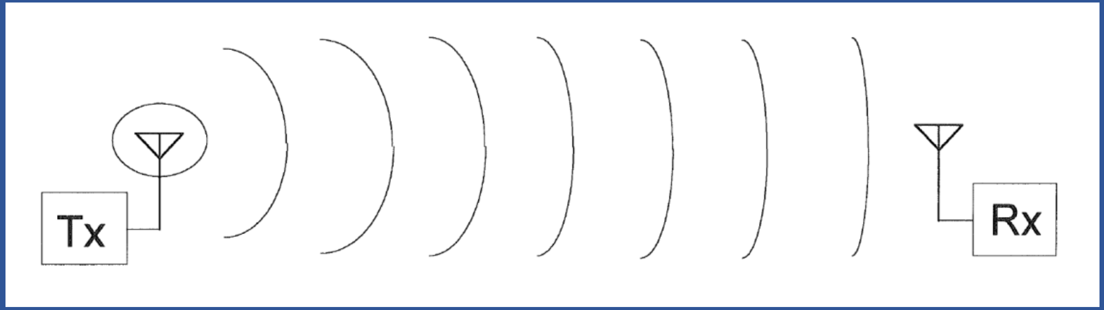
Assumes resonant antenna and free-space propagation, operating in the “far field”, with no obstructions or multipath …

Finding E and Vr at Receiver



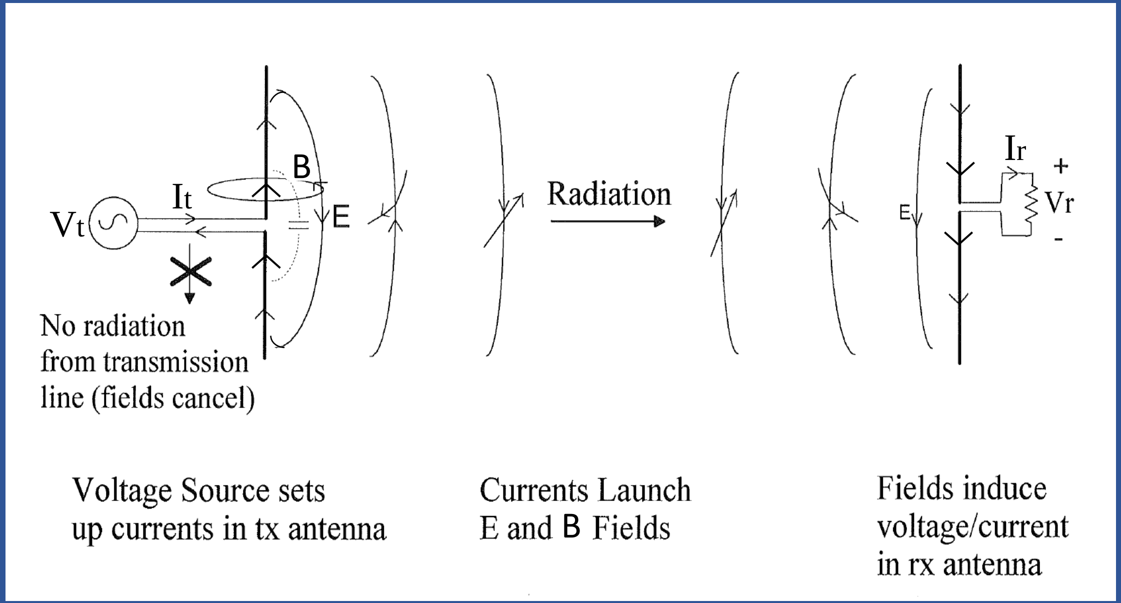
$$P_t = \frac{{V_t}^2}{R_{ant}}$$

$$\mathrm{P}_{density} = \frac{P_t\, G_t}{4\,\pi\, d^2} = \frac{|E|^2}{Z_o}$$

$$E = \sqrt{\frac{P_t\, G_t}{4\,\pi\, d^2}\; Z_o}$$

NOTE: E decreases as 1/d, not $1/d^2$

(… in free-space. See Episode 3 for path-loss exponent in terrestrial environments…)



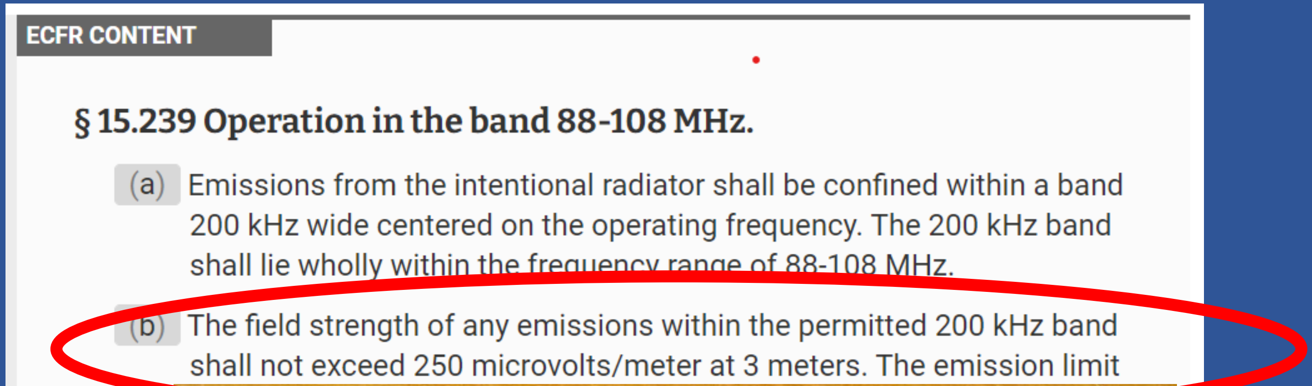
$$V_r = \mathrm{E}\; L_{eff}$$

Leff is effective length (or 'height') of antenna

For halfwave dipole, $L_{eff} = \frac{2}{\pi}\,\frac{\lambda}{2}$

Example: Field Strength Rules

For Unlicensed FM transmitters in the US, find maximum legal transmit power:



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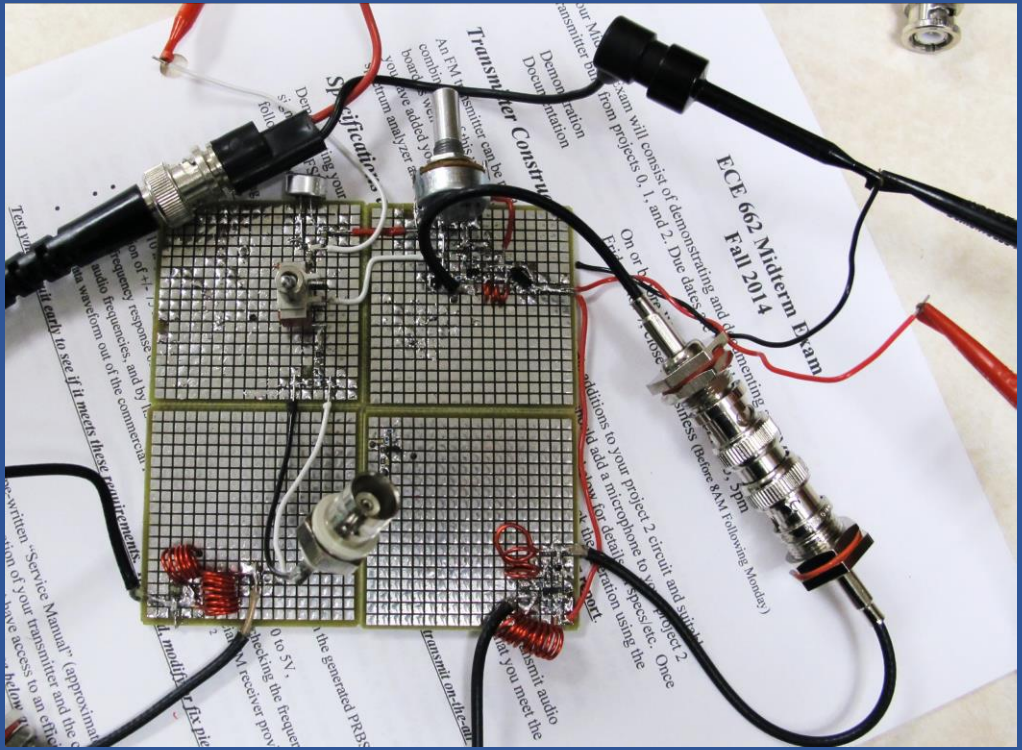
And with E=250uV/m, Zo = 377 Ohms, d=3m, and Gt=1.6 (dipole), we get max legal tx power (with halfwave dipole antenna) is

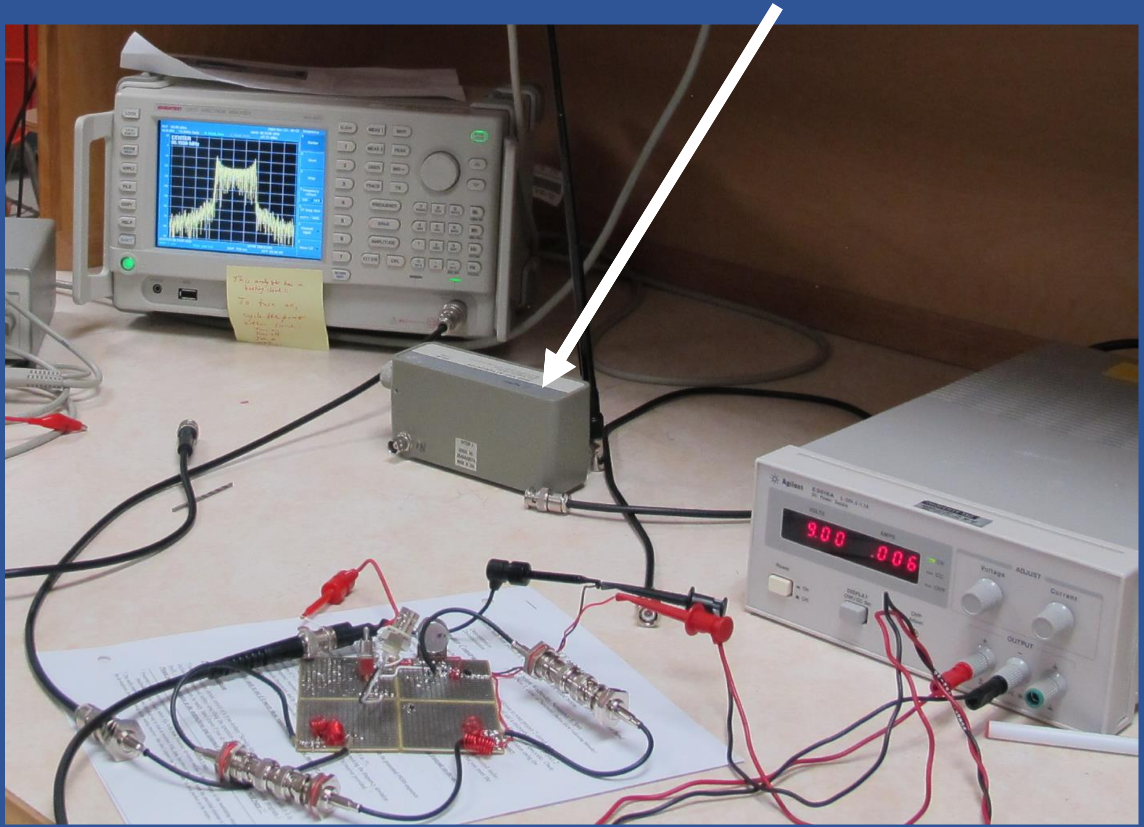
$$P_t = 11.6\, nW \;\; !!$$

$$(-49\, dBm \;\; !)$$

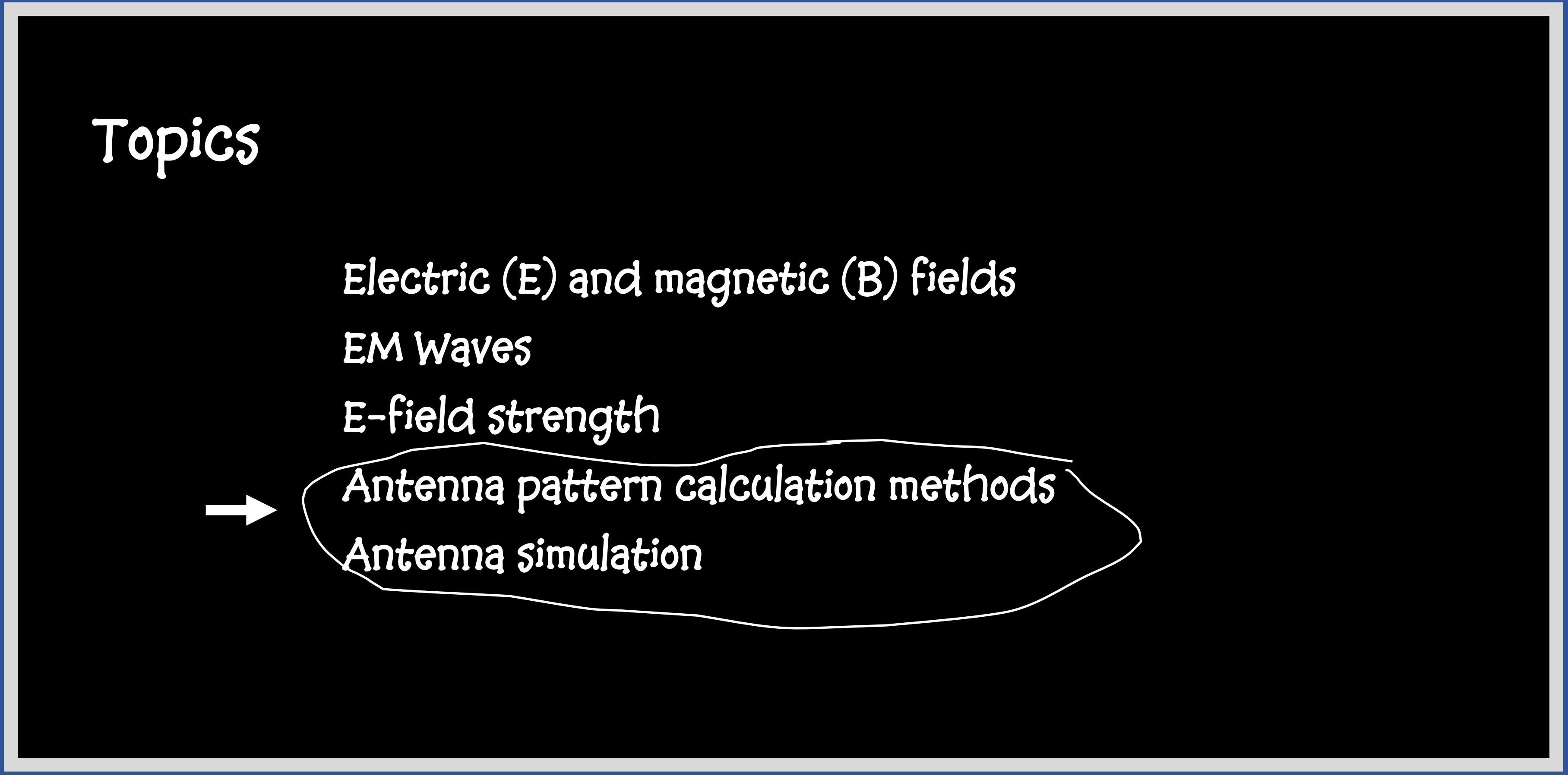
FM Transmitter Demo in ECE 662 Course



Antenna and 50 dB attenuator ☺



Topics



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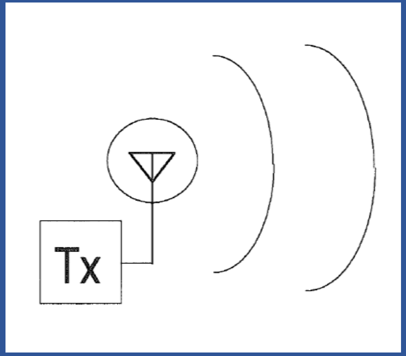
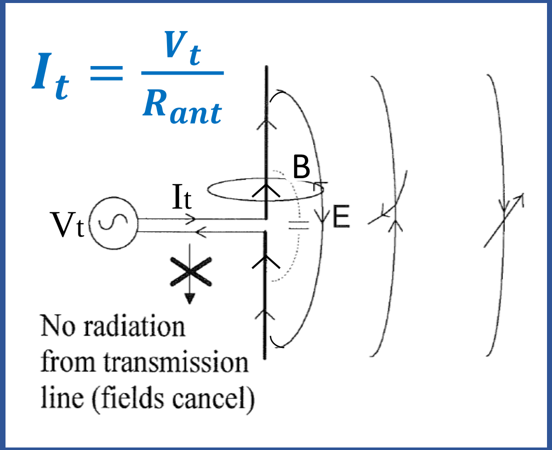
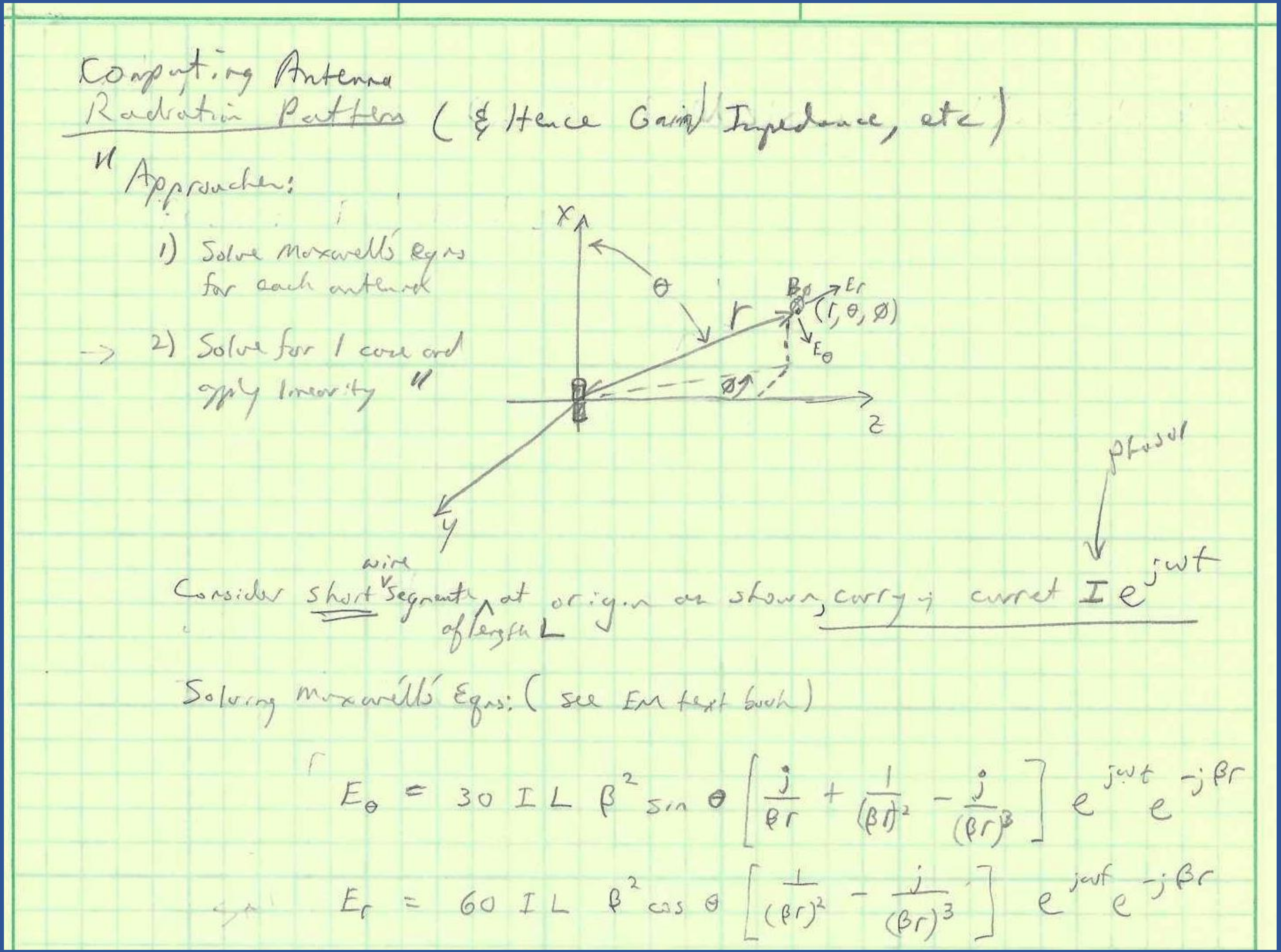
Far Field Pattern Calculation in ECE 764







Computing Antenna Radiation Pattern (& Hence Gain, Impedance, etc)

" Approaches:

1) Solve Maxwell's eqns for each antenna

→ 2) Solve for 1 case and apply linearity "

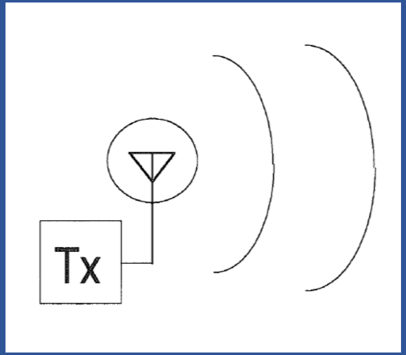
Consider short wire segment, of length L at origin as shown, carrying current $I e^{j\omega t}$

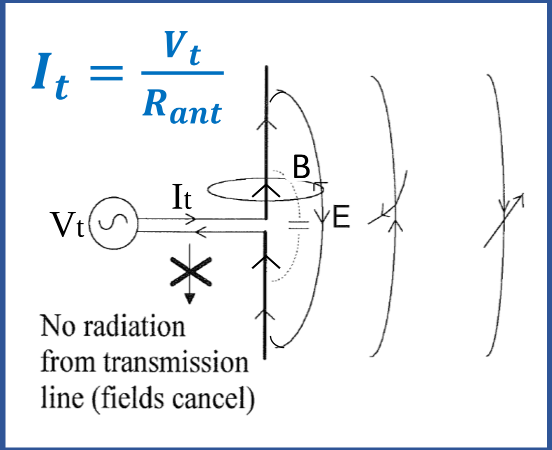
Solving Maxwell's Eqns: (see EM text book)

$$E_\theta = 30\, I L\, \beta^2 \sin\theta \left[\frac{j}{\beta r} + \frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3} \right] e^{j\omega t} e^{-j\beta r}$$

$$E_r = 60\, I L\, \beta^2 \cos\theta \left[\frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3} \right] e^{j\omega t} e^{-j\beta r}$$

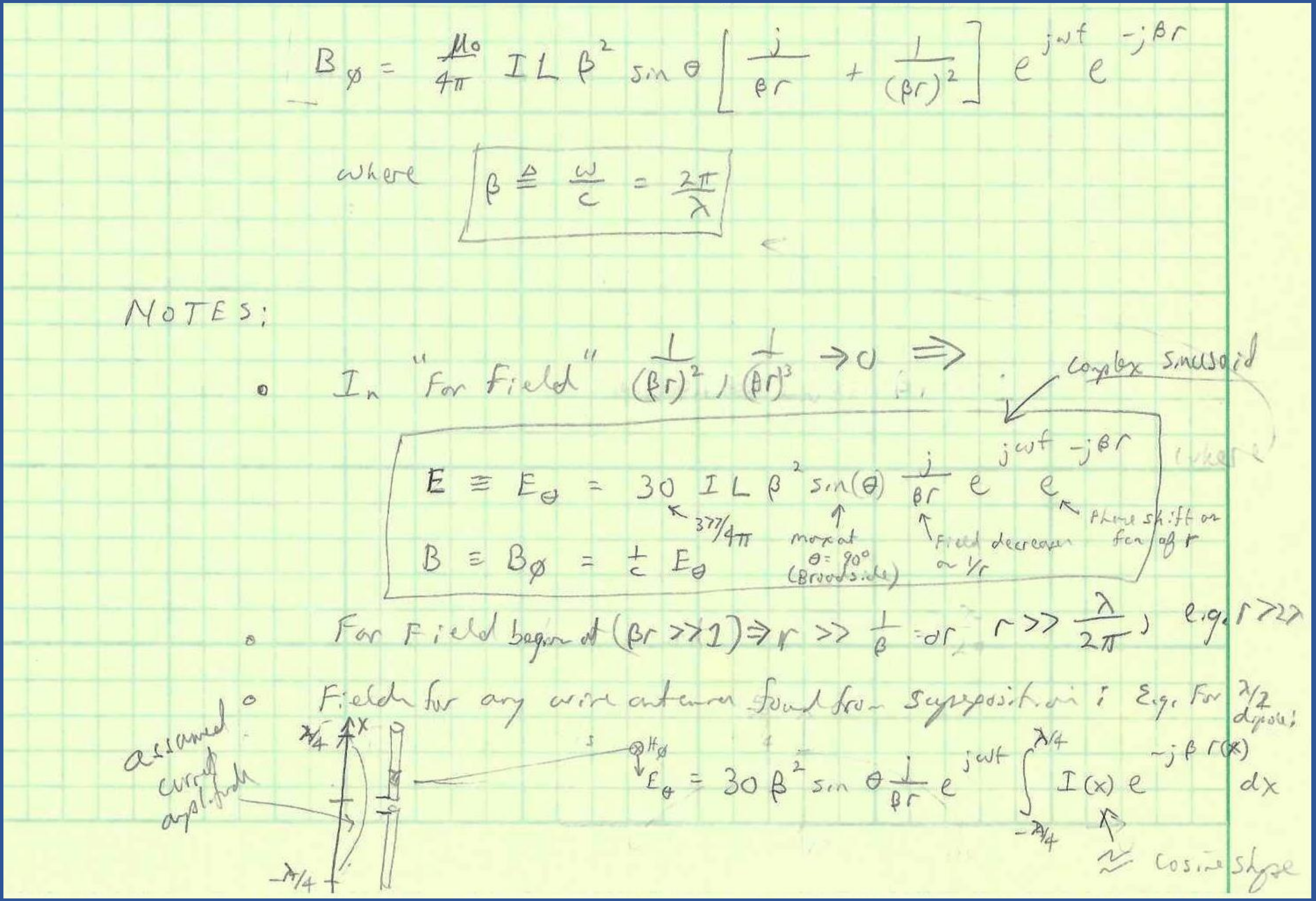
Far Field Pattern Calculation





$I_t = \frac{V_t}{R_{ant}}$

No radiation from transmission line (fields cancel)



$$B_\phi = \frac{\mu_0}{4\pi} I L \beta^2 \sin\theta \left[\frac{j}{\beta r} + \frac{1}{(\beta r)^2} \right] e^{j\omega t} e^{-j\beta r}$$

where $\boxed{\beta \triangleq \frac{\omega}{c} = \frac{2\pi}{\lambda}}$

NOTES:

- In "Far Field" $\frac{1}{(\beta r)^2}, \frac{1}{(\beta r)^3} \to 0 \Rightarrow$

$$\boxed{\begin{aligned} E \equiv E_\theta &= 30\, I L \beta^2 \sin(\theta) \frac{j}{\beta r} e^{j\omega t} e^{-j\beta r} \\ B \equiv B_\phi &= \frac{1}{c} E_\theta \end{aligned}}$$

complex sinusoid

377/4π

max at θ = 90° (Broadside)

Field decreases ∼ 1/r

Phase shift as fcn of r

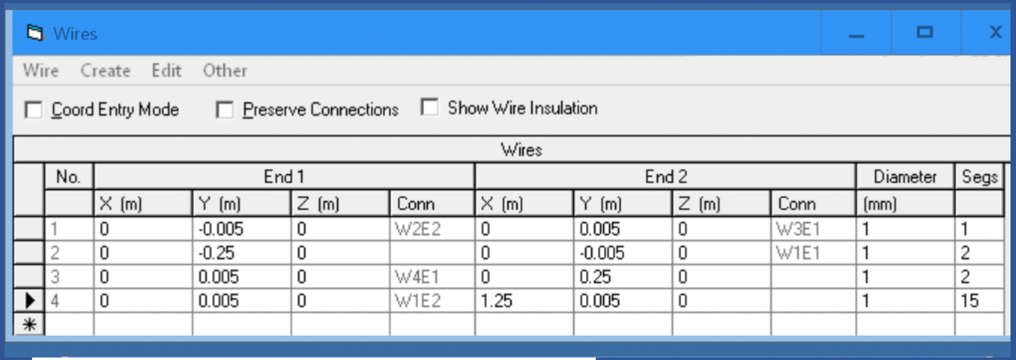
- Far Field begins at $(\beta r \gg 1) \Rightarrow r \gg \frac{1}{\beta}$ or, $r \gg \frac{\lambda}{2\pi}$) e.g. r >2
- Fields for any wire antenna found from superposition; E.g. For λ/2 dipole:

assumed current amplitude

$$E_\theta = 30 \beta^2 \sin\theta \frac{1}{\beta r} e^{j\omega t} \int_{-\lambda/4}^{\lambda/4} I(x)\, e^{-j\beta r(x)}\, dx$$

≈ cosine shape

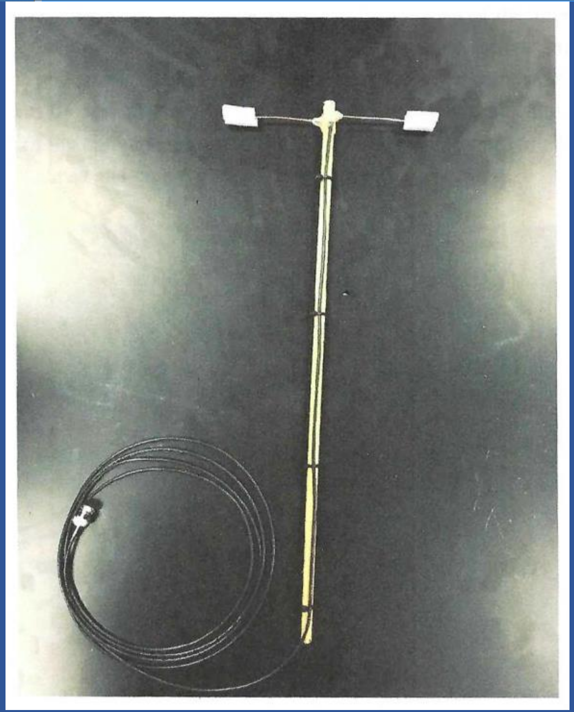
Antenna Simulation (with EZNEC) …

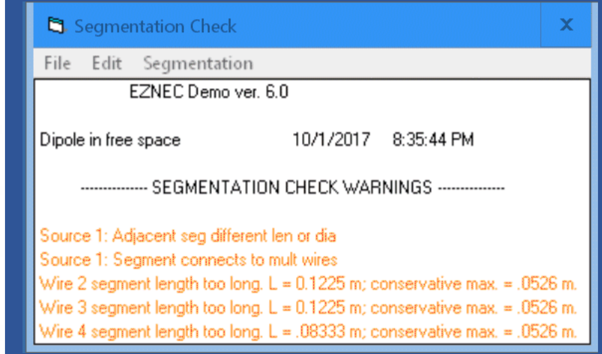


☐ Coord Entry Mode
☐ Preserve Connections
☐ Show Wire Insulation

Wires

No.	End 1				End 2				Diameter	Segs
	X (m)	Y (m)	Z (m)	Conn	X (m)	Y (m)	Z (m)	Conn	(mm)	
1	0	-0.005	0	W2E2	0	0.005	0	W3E1	1	1
2	0	-0.25	0		0	-0.005	0	W1E1	1	2
3	0	0.005	0	W4E1	0	0.25	0		1	2
▶ 4	0	0.005	0	W1E2	1.25	0.005	0		1	15
✱										



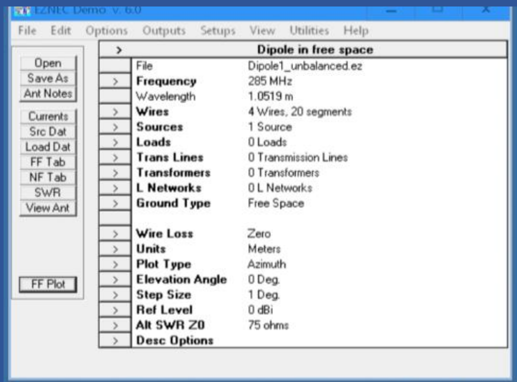


EZNEC Demo ver. 6.0

Dipole in free space 10/1/2017 8:35:44 PM

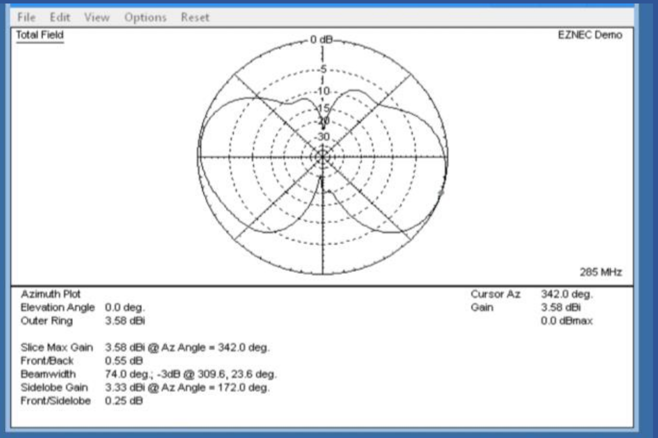
-------------- SEGMENTATION CHECK WARNINGS --------------

Source 1: Adjacent seg different len or dia
Source 1: Segment connects to mult wires
Wire 2 segment length too long. L = 0.1225 m; conservative max. = .0526 m.
Wire 3 segment length too long. L = 0.1225 m; conservative max. = .0526 m.
Wire 4 segment length too long. L = .08333 m; conservative max. = .0526 m.



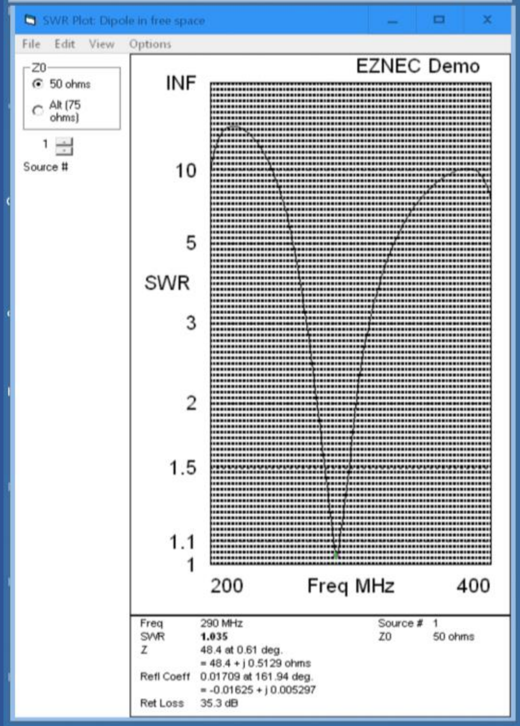
Dipole in free space

File	Dipole1_unbalanced.ez
Frequency	285 MHz
Wavelength	1.0519 m
Wires	4 Wires, 20 segments
Sources	1 Source
Loads	0 Loads
Trans Lines	0 Transmission Lines
Transformers	0 Transformers
L Networks	0 L Networks
Ground Type	Free Space
Wire Loss	Zero
Units	Meters
Plot Type	Azimuth
Elevation Angle	0 Deg.
Step Size	1 Deg.
Ref Level	0 dBi
Alt SWR Z0	75 ohms
Desc Options	



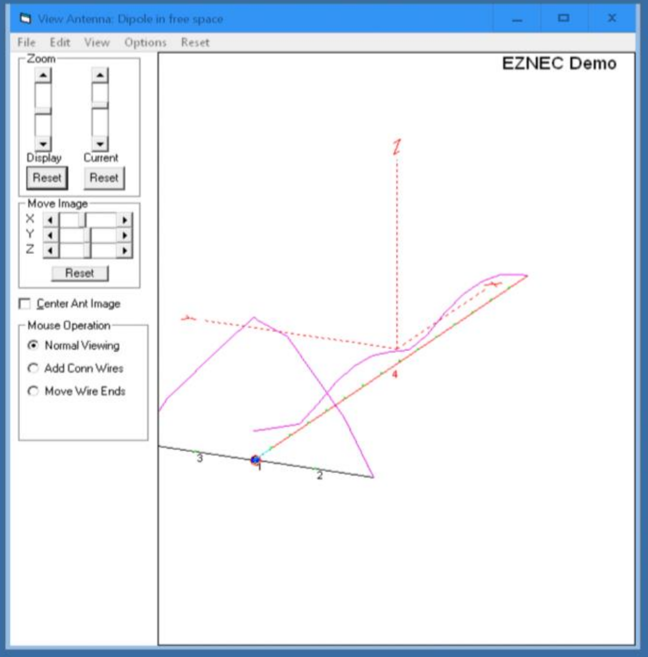
Azimuth Plot		Cursor Az	342.0 deg.
Elevation Angle	0.0 deg.	Gain	3.58 dBi
Outer Ring	3.58 dBi		0.0 dBmax

Slice Max Gain	3.58 dBi @ Az Angle = 342.0 deg.
Front/Back	0.55 dB
Beamwidth	74.0 deg.; -3dB @ 309.6, 23.6 deg.
Sidelobe Gain	3.33 dBi @ Az Angle = 172.0 deg.
Front/Sidelobe	0.25 dB



Z0: ● 50 ohms ○ Alt (75 ohms)

Freq	290 MHz	Source #	1
SWR	**1.035**	Z0	50 ohms
Z	48.4 at 0.61 deg. = 48.4 + j 0.5129 ohms		
Refl Coeff	0.01709 at 161.94 deg. = -0.01625 + j 0.005297		
Ret Loss	35.3 dB		



☐ Center Ant Image

● Normal Viewing
○ Add Conn Wires
○ Move Wire Ends

Future Topics

Upcoming episodes

- Far field calculation and simulation
- Reflection of EM Waves in environment
- Antenna types, gain, impedance, and polarization
- Counterpoise, baluns, and chokes
- Phase, superposition, and beamforming…

Thanks for Watching

Today’s Final Topic

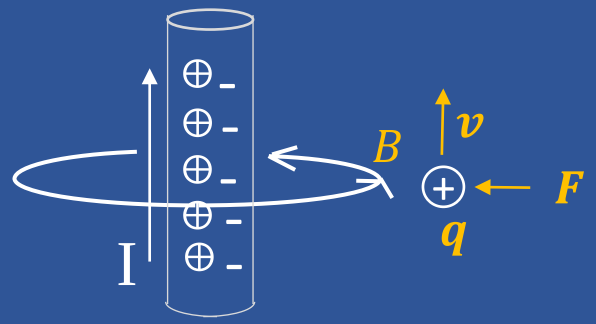
A brief look at the physics behind all this…

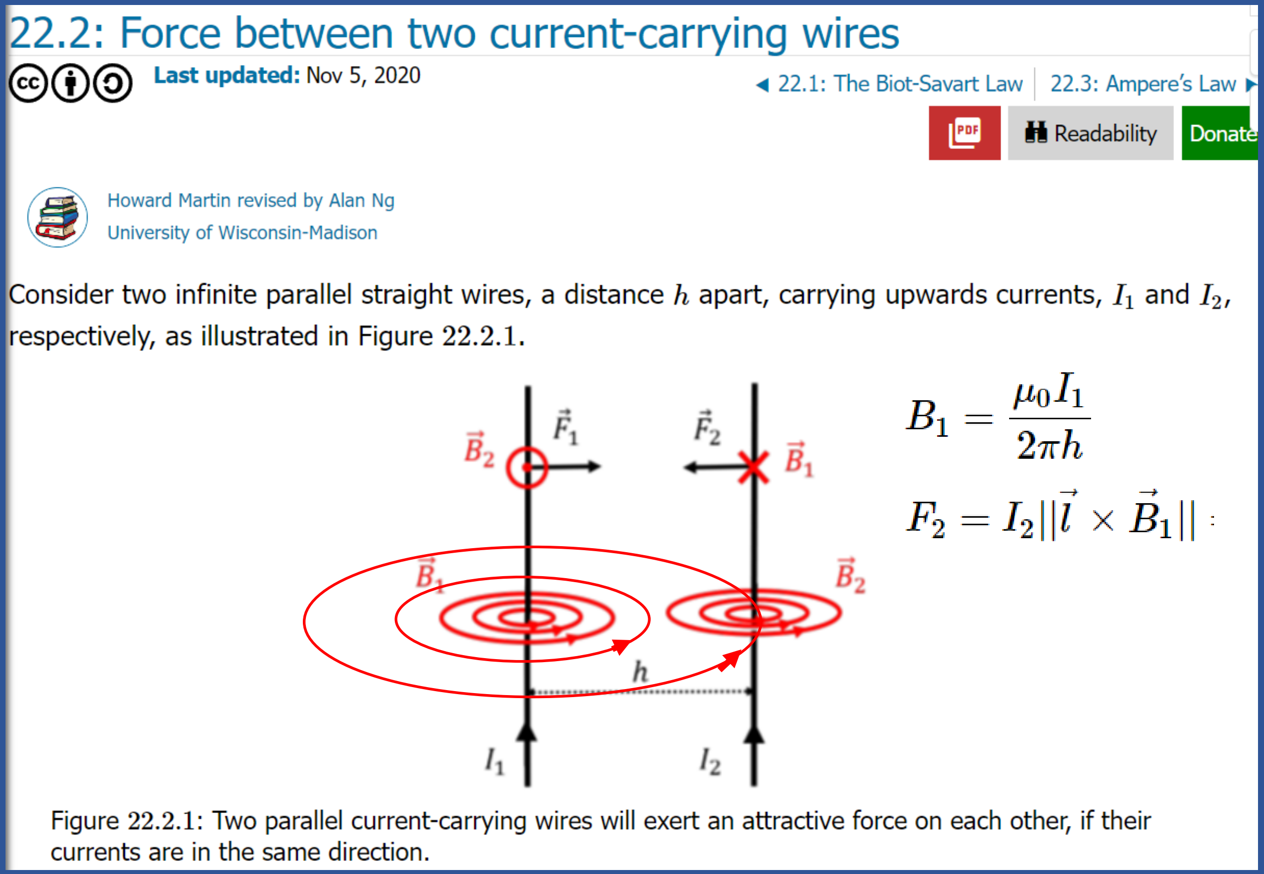
→ What “are” E, B and EM fields ?

Magnetic Fields Revisited

Force on a (moving) charge q in presence of B is:

$$\boldsymbol{F} = q\,(\boldsymbol{v} \times \boldsymbol{B})$$





22.2: Force between two current-carrying wires

Last updated: Nov 5, 2020

◂ 22.1: The Biot-Savart Law | 22.3: Ampere's Law ▸

Readability Donate

Howard Martin revised by Alan Ng
University of Wisconsin-Madison

Consider two infinite parallel straight wires, a distance h apart, carrying upwards currents, I_1 and I_2, respectively, as illustrated in Figure 22.2.1.

$$B_1 = \frac{\mu_0 I_1}{2\pi h}$$

$$F_2 = I_2 ||\vec{l} \times \vec{B}_1||$$

Figure 22.2.1: Two parallel current-carrying wires will exert an attractive force on each other, if their currents are in the same direction.

https://phys.libretexts.org/Bookshelves/University_Physics/Book%3A_Introductory_Physics_-_Building_Models_to_Describe_Our_World_(Martin_Neary_Rinaldo_and_Woodman)/22%3A_Source_of_Magnetic_Field/22.02%3A_Force_between_two_current-carrying_wires

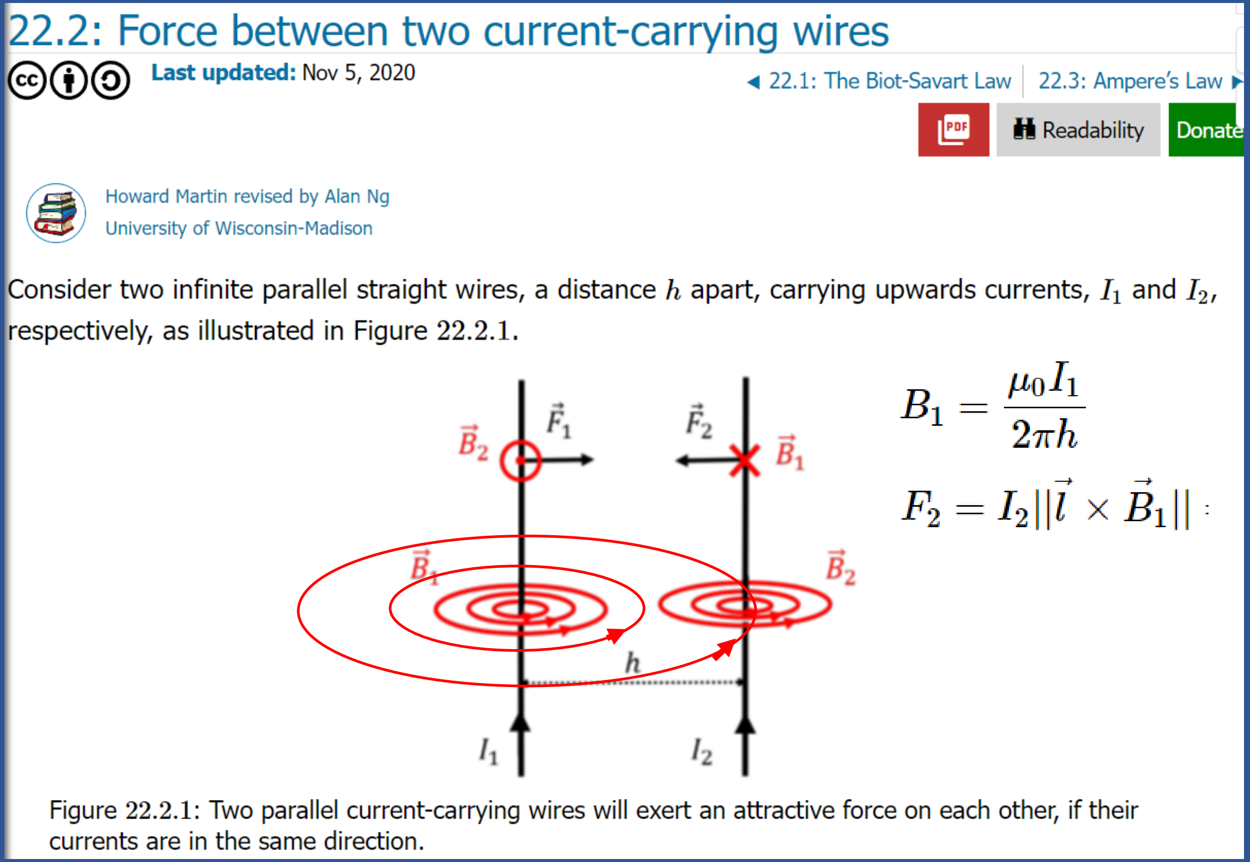
Where Does Force Come From ?

Coulombs Law + Relativity !

B Fields originate from ***moving charges***

And so do E-fields ☺

It’s really just Coulombs Law (with relativistic length dilation)



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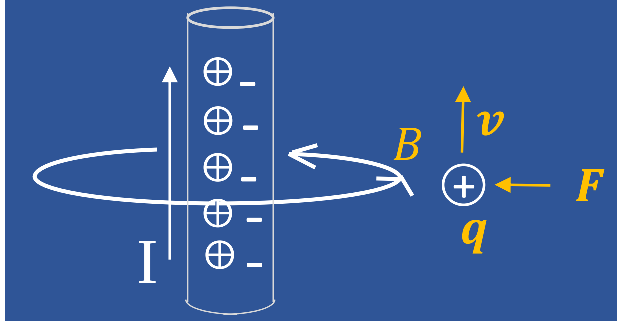
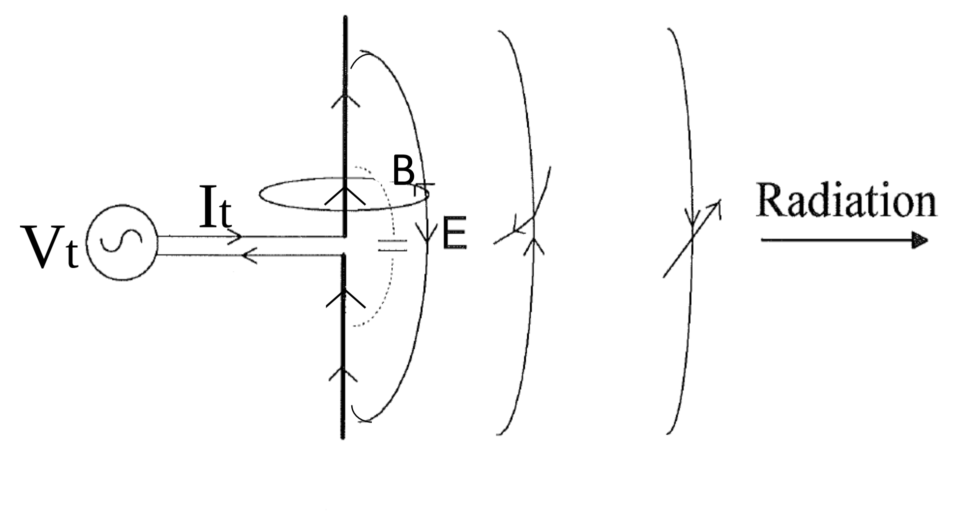
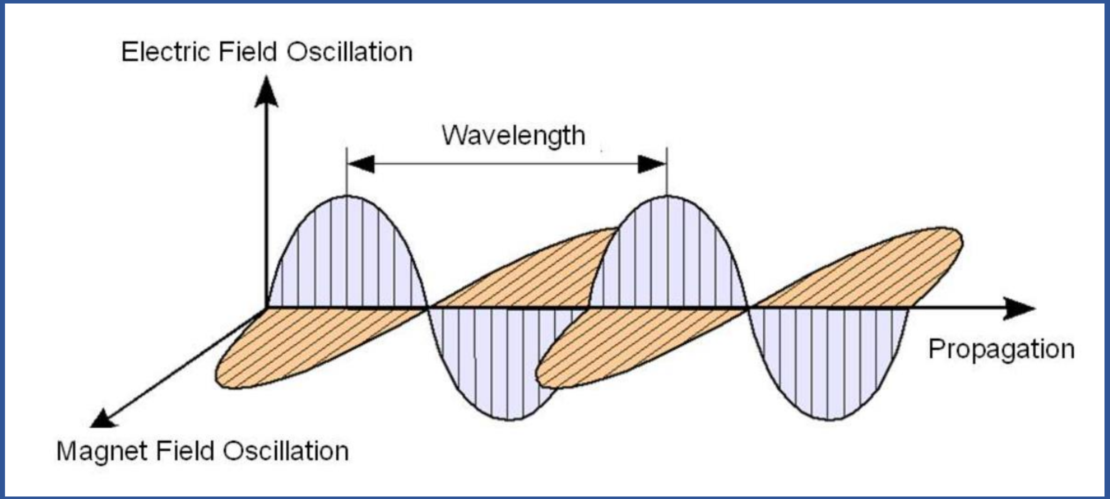


And… An AC current (***accelerating*** *charges*) creates a time/space-varying ***EM field***, which propagates at velocity c through empty space …



From: http://cleanenergywiki.org/index.php?title=File:Emwavepropagation.jpg



$$\frac{\Delta E_x}{\Delta z} = -\frac{\Delta B_y}{\Delta t}$$

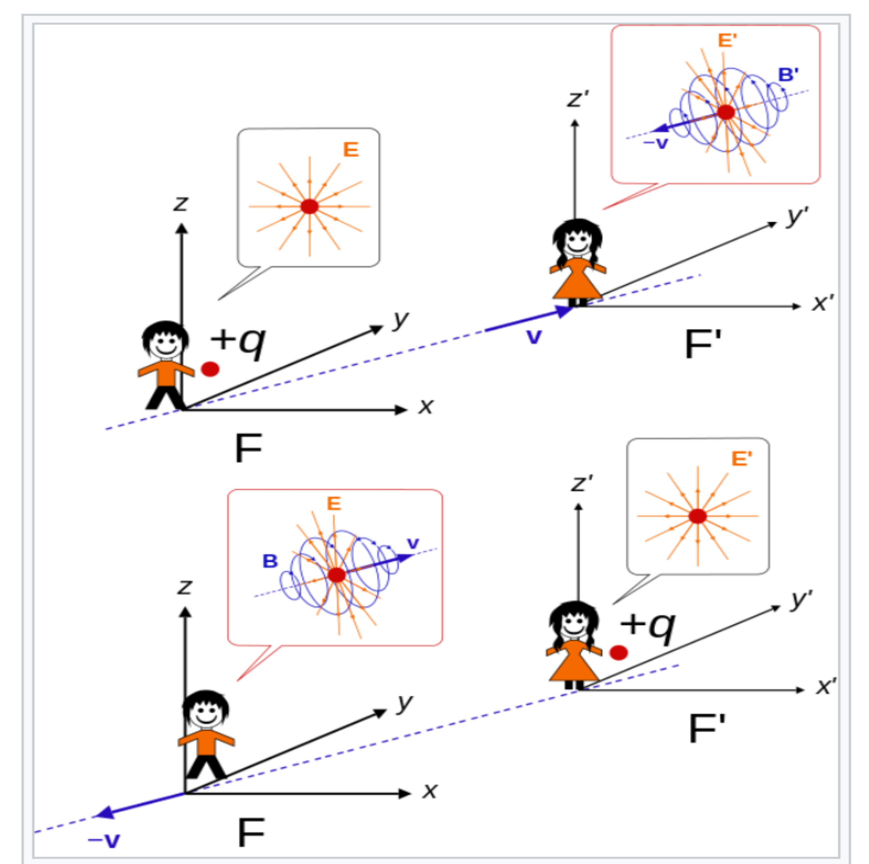
$$-\frac{\Delta B_y}{\Delta z} = \mu_o \varepsilon_o \frac{\Delta E_x}{\Delta t}$$

$$E_x = E_o \cos\left(2\pi f\left(t - \frac{z}{c}\right)\right)$$ and $$B_y = \frac{1}{c} E_x$$

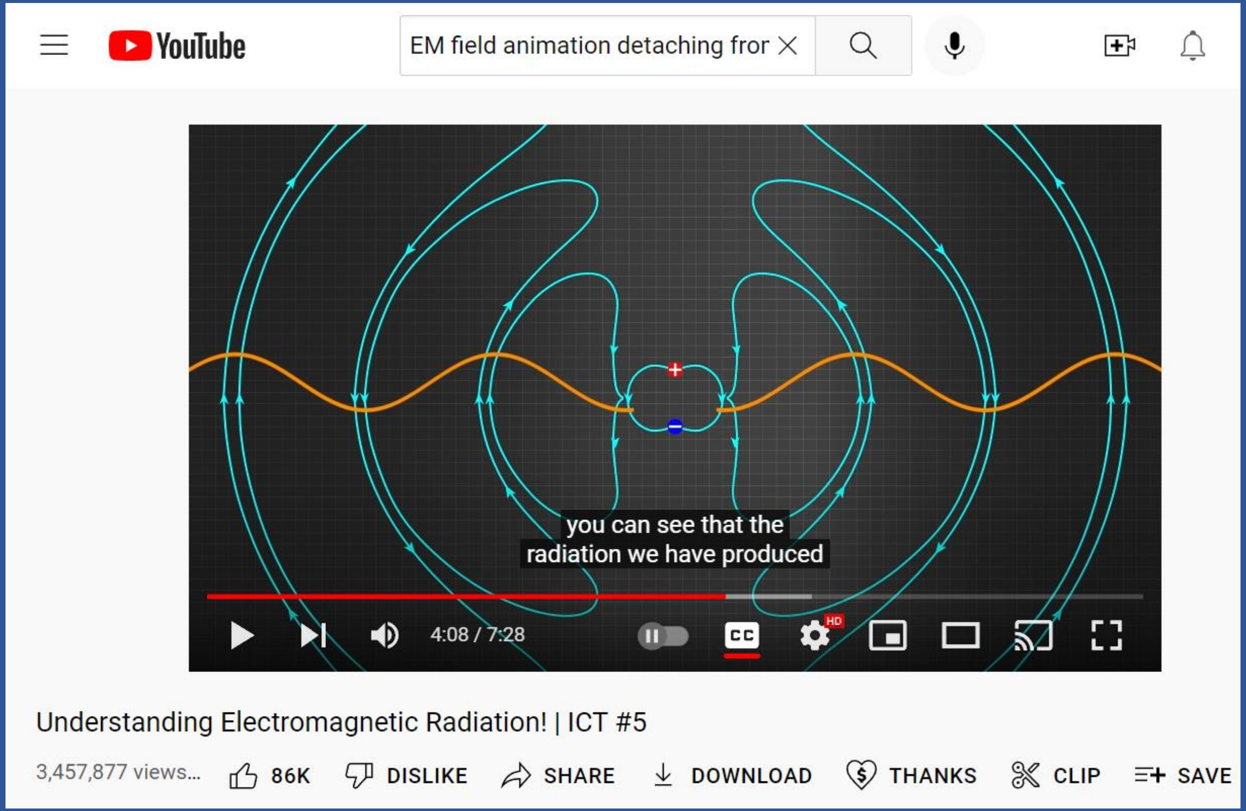
With $c = \sqrt{\frac{1}{\mu_o\,\varepsilon_o}} = 2.998E8$ meters/second

Other Explanations/views …

From **Joules-Bernoulli** equation discussion in:
https://en.wikipedia.org/wiki/Classical_electromagnetism_and_special_relativity



Lorentz boost of an electric charge.



you can see that the
radiation we have produced

Understanding Electromagnetic Radiation! | ICT #5

3,457,877 views...

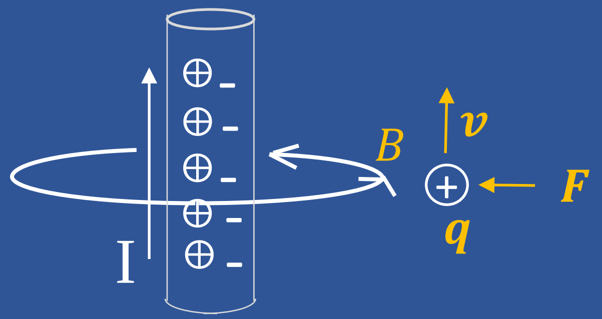
https://www.youtube.com/watch?v=FWCN_uI5ygY

Thanks for Watching

…all the way to the end ☺

But What “is” a Magnetic Field ?

B field “curls” around a current



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Why ??

Coulombs Law + Relativity !

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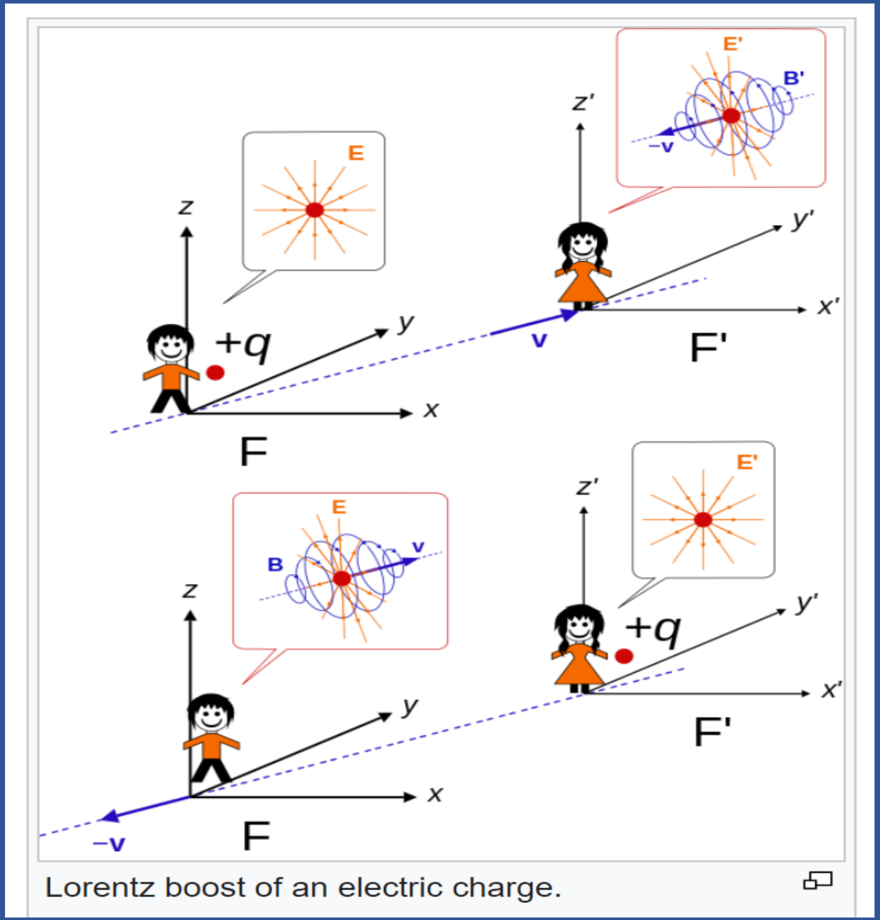

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