EE2632 通信信号传输 期末复习笔记

一、电磁场基础知识

1. 传输线理论 → 反射系数 (reflection coefficient)

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Z_L: 天线的负载阻抗 (load impedance)

Z_0: 传输线上的阻抗 (characteristic impedance)

2. 平面波理论 (Plane wave theory)

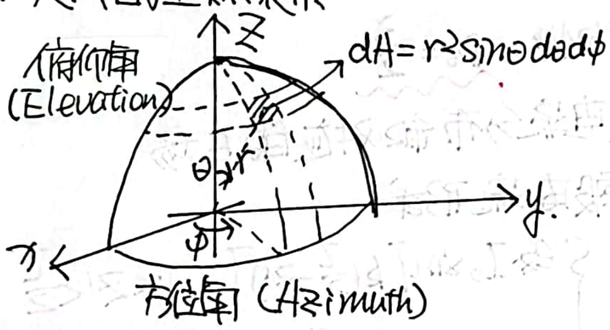
(1) 波阻抗

$\eta = \sqrt{\frac{\mu}{\varepsilon}}$ 真空中: $\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi$

(2) 波数: $k = \omega\sqrt{\mu_0\varepsilon_0} = \frac{2\pi}{\lambda}$

二、天线的基本参数

1. 天线的坐标表示



φ 从 x 轴指向 y 轴

θ 从 z 轴正方向指向 z 轴负方向

其中, 若题目中没有给出情况

$$\begin{cases} \phi: 0 \to 2\pi \\ \theta: 0 \to \pi \end{cases}$$

2. 天线的方向图 (Radiation pattern)

Eg: 求半功率波束宽度 (half-power beamwidth)

- $U(\theta_h) = \frac{1}{2}U$

  $U(\theta_{max}) = U|_{max}$

- $HPBW = 2|\theta_{max} - \theta_h|$

3. 辐射功率密度 (Radiation power density)

- 表示: W_{rad}, S_{av} (w/m^2)

4. 辐射强度 (Radiation intensity)

$$U = r^2 \cdot W_{rad}$$

5. 求总功率

- $P_{rad} = \oiint_S W_{rad} \cdot dA = \int_0^{2\pi}\int_0^{\pi} W_{rad}\, r^2 \sin\theta\, d\theta\, d\phi$

- $P_{rad} = \oiint_\Omega U\, d\Omega = \int_0^{2\pi}\int_0^{\pi} U \sin\theta\, d\theta\, d\phi$

其中 $dA = r^2 \sin\theta\, d\theta\, d\phi$ 面积元

$d\Omega = \sin\theta\, d\theta\, d\phi$ 立体角

6. 方向性 (directivity)

$$D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}}$$

然 通常求最大方向性

$$D_0 = \frac{4\pi U_{max}}{P_{rad}}$$

7. 天线效率(Antenna efficiency).

$$e_0 = e_r \cdot e_c \cdot e_d = e_r \cdot e_{cd}$$

• $e_r = 1-|\Gamma|^2$ 反射效率

$$\Gamma = \frac{Z_{in}-Z_0}{Z_{in}+Z_0}$$

Z_{in}: 输入阻抗 (Input impedance)

Z_0: 传输线特征阻抗 (Characteristic impedance of the transmission line)

• e_{cd}: 天线的辐射效率 (Radiation efficiency) (dimensionless).

$$e_{cd} = \frac{P_{rad}}{P_{in}} = \frac{R_r}{R_r+R_L}$$

R_r: Radiation ~~impe~~ resistance

R_L: Loss resistance

8. 天线增益 (Gain)

(1)

$$G_0 = e_{cd} \cdot D_0$$

↓ 对数下

$$G_0(dB) = 10\log(e_{cd}) + 10\log(D_0)$$

(2) Realized Gain

$$G_{re} = e_0 \cdot D_0 = e_r \cdot e_{cd} \cdot D_0$$

在求得 G_0 的基础上乘一个 e_r.

9. 极化 (Polarization)

线极化: linear polarization

圆极化: Circular polarization

椭圆极化: Elliptical polarization

10. 有效面积

$$A_{em} = \frac{\lambda^2}{4\pi} D_0$$

↓

各向同性天线的有效面积

~~天线~~

三、偶极子天线 (Dipole)

1、辐射阻抗 (Radiation impedance)

$$P_{rad} = 40\pi^2 I^2 \left(\frac{l}{\lambda}\right)^2$$

$$P_r = \frac{1}{2}|I|^2 R_r$$

$$\therefore R_r = \frac{2P_r}{I^2} = \boxed{80\pi^2 \left(\frac{l}{\lambda}\right)^2}$$

2、方向性: $D_0 = \frac{3}{2}$

3、画电流分布和对应的E场

• 一般电流形式

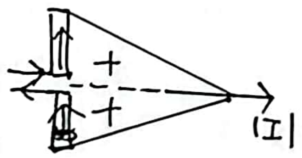
$$\vec{I_e} = \begin{cases} e_z I_0 \sin\left[k\left(\frac{l}{2}-z'\right)\right], & 0 < z' < \frac{l}{2} \\ e_z I_0 \sin\left[k\left(\frac{l}{2}+z'\right)\right], & -\frac{l}{2} < z' < 0 \end{cases}$$

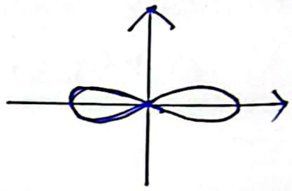
• 半波长偶极子电流 (简化)

$$I_z(z) = I \cdot \cos(kz'), \quad -\frac{\lambda}{4} \le z \le \frac{\lambda}{4}$$

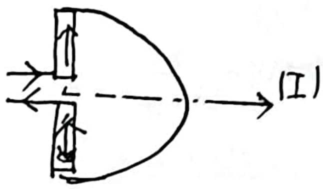
电流分布　　　　　　　　　　E场

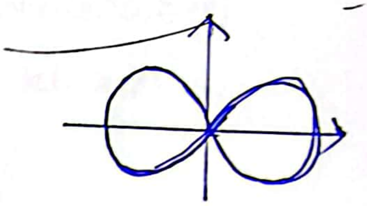
① $l \ll \lambda$



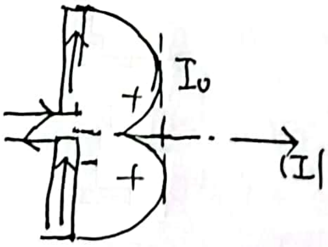


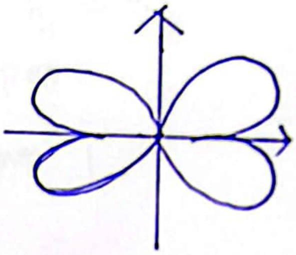
② $l=\frac{\lambda}{2}$



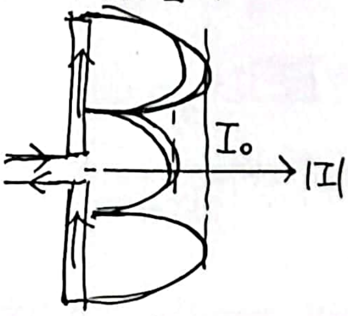


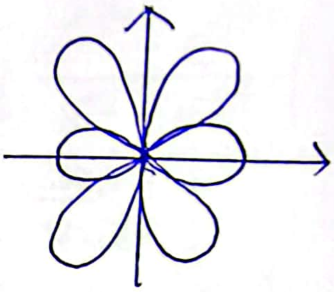
③ $\frac{\lambda}{2}<l<\lambda$.





④ $\lambda<l<\frac{3}{2}\lambda$.





4. 辐射阻抗Rr和输入电阻Rin.

$$R_{in}=\left[\frac{I_0}{I_{in}}\right]^2 R_r=\frac{R_r}{\sin^2(\frac{kl}{2})}$$

当 $l=\frac{\lambda}{2}$ 时. $R_{in}=R_r$.

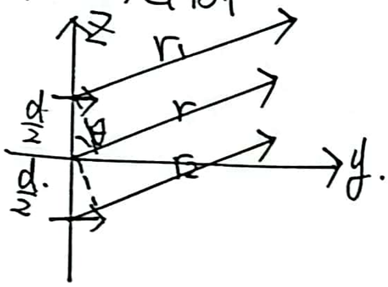
$\Gamma=\frac{Z_L-Z_0}{Z_L+Z_0}$ 阻抗匹配

此时天线的效率最高

• 但当~~在~~ $l=1.5\lambda, 2.5\lambda \ldots$ 时, 依然有 $R_{in}=R_r$.

四、天线阵列.

1、关于二元阵列



For phase variations $\begin{cases} r_1=r-\frac{d}{2}\cos\theta \\ r_2=r+\frac{d}{2}\cos\theta \end{cases}$

For amplitude variations $r \approx r_1 \approx r_2$

$$E_t=E_1+E_2$$
$$=E_0\cdot\frac{e^{-jkr_1}}{r_1}+E_0\cdot\frac{e^{-jkr_2}}{r_2}$$
$$=E_0\left[\frac{e^{-jk(r-\frac{d}{2}\cos\theta)}}{r}+\frac{e^{-jk(r+\frac{d}{2}\cos\theta)}}{r}\right]$$
$$=\frac{E_0e^{-jkr}}{r}\cdot 2\cos\left(\tfrac{1}{2}kd\cos\theta\right)$$

$\therefore AF_{normalized}=\cos(\frac{1}{2}kd\cos\theta)$.

• 若求nulls. 令 $AF=0$

若求maxima. 令 $AF=1$.

2、多元阵列——公式推导 ☆

The array of identical isotropic elements with a progressive phase is referred to as a uniform array. The total field is be:

$$E_t=E_1+E_2+E_3+\cdots+E_n=\sum_n E_n\cdot\frac{e^{-jkr_n}}{r_n}$$

For far-field ~~variations~~ observations.

$\begin{cases} r_n=r+nd\cos\theta & \text{For phase variations} \\ r_n \approx r & \text{For amplitude variations} \end{cases}$

For an isotropic element. the total field is obtained by multiplying the array factor of the isotropic sources by the field of a single element. The array factor can be calculated as:

$$E_t = E_0 \times AF$$

$$\therefore AF = 1 + e^{+j(kd\cos\theta+\beta)} + e^{+2j(kd\cos\theta+\beta)} + \cdots + e^{+j(N-1)(kd\cos\theta+\beta)}$$

$$= \sum_{n=1}^{N} e^{+j(N-1)(kd\cos\theta+\beta)}$$

Let $\psi = kd\cos\theta + \beta$

$$\therefore AF = \sum_{n=1}^{N} e^{+j(N-1)\psi}$$

Multiplying both side by $e^{j\varphi}$.

$$AF \cdot e^{j\varphi} = \sum_{n=1}^{N} e^{+jN\varphi}$$

$$AF(e^{j\varphi}-1) = e^{+jN\varphi} - 1$$

$$\therefore AF = \frac{e^{+jN\varphi}-1}{e^{j\varphi}-1}$$

$$= e^{+j\left[\frac{N-1}{2}\right]\varphi}\left[\frac{e^{+j\frac{N}{2}\varphi} - e^{-j\frac{N}{2}\varphi}}{e^{j\frac{\varphi}{2}} - e^{-j\frac{\varphi}{2}}}\right]$$

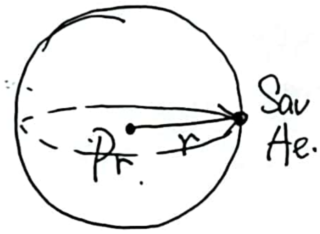
$$= e^{+j\left[\frac{N-1}{2}\right]\varphi}\left[\frac{\sin(\frac{N}{2}\varphi)}{\sin(\frac{1}{2}\varphi)}\right]$$

If the reference point is the physical ~~centre~~ center of the array, the array factor is.

$$AF = \left[\frac{\sin(\frac{N}{2}\varphi)}{\sin(\frac{1}{2}\varphi)}\right]$$

五、电波传播基本原理

1、自由空间中的传播损失.



~~Ae:~~ P_L: 接收功率

$$S_{av} = \frac{P_r}{4\pi r^2} \qquad A_e = \frac{\lambda^2}{4\pi}.$$

• 接收功率: $P_L = S_{av} \cdot A_e = \left(\frac{\lambda}{4\pi r}\right)^2 \cdot P_r$

• 自由空间中损失为.

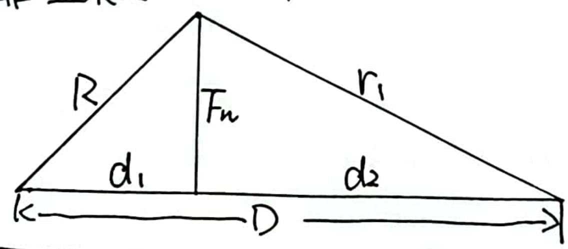
$$L_{fs}(dB) = 10\log\left(\frac{P_r}{P_L}\right).$$

$$L_{fs}(dB) = 32.45 + 20\log f(MHz) + 20\log r(km)$$

2、Friis 自由空间通信链路公式

$$P_L = \left(\frac{\lambda}{4\pi r}\right)^2 \cdot P_{in} \cdot G_t \cdot G_r.$$

3、菲涅尔区 (Fresnel zone)



$$\sqrt{F_n^2+d_1^2} + \sqrt{F_n^2+d_2^2} - D = n\cdot\frac{\lambda}{2}.$$

当 $d_1 d_2 \gg \lambda$ 时.

$$F_n = \sqrt{n \cdot \frac{d_1 d_2 \lambda}{d_1+d_2}}$$

$n=1$ 且, $d_1 = d_2 = \frac{D}{2}$ 时, 称第一菲涅尔区

菲涅尔半径 $R = \frac{1}{2}\sqrt{\lambda D}$

~~横截面一般不应超过整个菲涅尔区~~

障碍物高度要在R的20%以内

六、地波传播 (Surface wave)

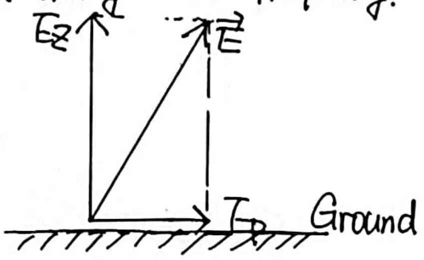
解释~~地~~地波传播过程中的倾斜效应

Sommerfeld and Norton derived expressions for the ground-wave field-strength components above a finitely conducting plane earth due to a short vertical current ~~elemen~~ element. When space wave approach zero, the surface wave dominates, and ground-wave field-strengths are:

$$E_z = j60kl\,dl\cdot(1-u^2+u^4)\cdot F\cdot\frac{e^{-jkr}}{r}$$

$$E_p = j\cdot 30kl\cdot dl\left\{u\cdot\sqrt{(1-u^2)(2-u^2+u^4)}\right\}\cdot F\cdot\frac{e^{-jkr}}{r}$$

The radial component given by equation E_p is small relative to the vertical component describe by equation E_z. The phase relationship is such that the modest wavefront tilt is forward in the direction of propagation. The degree of tilt depends on ground conductivity and frequency.



七、天波传播

1、临界频率

$$f_c(\mathrm{MHz}) = 9\sqrt{N}$$

N：电子密度

2、最大可用频率 (Maximum usable frequency)

$$MUF = f_c \times \sec\varphi_i$$

φ_i：入射角_辐射俯仰角

elevation angle of radiation

3、最佳使用频率 (Optimum usage frequency).

$$MUF = f_c \times \sec 74^\circ = 3.6 f_c$$

切向发射，天线仰角 $\Delta = 0^\circ$

$$OUF = MUF \times (70\% \sim 80\%)$$

若题目中没有给百分比，默认取80%.

八、移动通信中的无线电传播

1、分集技术 (Diversity approaches).

(1) Space diversity:

Multiple ~~ant~~ antenna at different positions to receive signals

(2) Angular diversity.

Using multi-beam antenna at different receiving ~~angu~~ angle.

(3) Frequency diversity

Using various frequency to receive signals.

(4) Polarization diversity

Using cross-polarization to receive signals.

(5) Time diversity

Retransmit the same signals multiple times in different time intervals.

2、通信链路

接收的能量等于发射的能量加上传输增益，减去传输损失。

传输损失小的一方覆盖更大，最终链路的覆盖由损失

(1) 下行链路

$P_{rM}=P_{tB}-L_c-L_d-L_{fB}-L_{fM}-L_p+G_t+G_r$

$P_{rs}+FM=P_{tB}-L_c-L_d-L_{fB}-L_{fM}-L_p+G_t+G_r$

(2) 上行链路

$P_{rB}=P_{tM}-L_d-L_{fB}-L_{fM}-L_p+G_t+G_r$

$P_{rs}+FM=P_{tM}-L_d-L_{fM}-L_{fB}-L_p+G_t+G_r$

[注]：
- L_c：合路器损耗 ~~Couplex~~ Coupler.
- L_{fB}、L_{fM}：馈线损耗，feeder.
- L_d：双工器损耗，Duplexer.

九、~~各类~~ 典型天线特点

1. 单极子天线 (Monopole antenna)

(1) 线天线 (2) 窄带天线 (3) 方向性弱

2. 八木天线 (Yagi-Uda antenna)

(1) 线天线 (2) 窄带天线

3. 等角螺旋天线 (Equiangular helix ~)

(1) 非频天线 (2) 圆极化

(3) 两臂视为变形的传输线，臂上电流沿线边传输、边辐射，边衰减

4. 对数周期天线 (Log-periodic ~)

(1) 非频变天线 (2) 线极化

(3) 方向性不是很强

5. 喇叭天线 (horn ~)

(1) 面天线 (2) 线极化

6. 抛物面天线 (reflector ~)

(1) 面天线 (2) 线极化

特殊天线的参数分析

天线类型	极化方式	增益	带宽	备注
单极天线（monopole antenna）	线极化	增益很低	窄带	线天线
喇叭天线（horn antenna）	线极化	增益很高（25dBi）	宽频带	
八木天线（Yagi-Uda antenna）	线极化	增益高	窄带	线天线
对数周期天线（Log-periodic antenna）	线极化	增益中等（8-11dBi）	宽频带	非频变天线
等角螺旋天线（Equiangular helix antenna）	圆极化	增益高	宽频带	非频变天线
抛物面天线（Reflector antenna）	线极化	增益高	窄带*	

- 八木天线：增益非常高、体积稍大、方向性强[1]。
- 对数周期天线：超宽带天线，带宽覆盖非常宽，带宽可达10:1[1]。
- 抛物面天线：增益高、方向性强、体积小，常用于卫星通信、雷达等领域[2]。
- 喇叭天线：工作频带宽，体积较大，方向性不及抛物面天线尖锐[2]。
- 等角螺旋天线：增益高、方向性强、体积小，常用于卫星通信、雷达等领域[3]。
- 单极天线：增益低，但是可以实现全向辐射[3]。