EE540 Advance Electromagnetic Theory & Antennas

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Slot antennas

- ***Applications:***
- Low-profile or flush mountings such as in high-speed aircrafts
- ***Analysis:***
- Consider complimentary forms such as strips or wires
- Impedances can be found by applying extension of Babinet's (Ba-bi-nay's) principle by Henry Booker
- Patterns can be found by applying duality theorem
- ***Babinet's principle in optics:***
- The field at any point behind a plane having a screen,
- if added to the field at the same point
  - when the complementary screen is substituted
- is equal to the field when no screen is present

Slot antennas

Fig. Illustration of Babinet's (Ba-bi-nay's) Principle

- Assume screen is perfectly absorbing
- Arrangement of a source

& two imaginary planes: Ps and Po

- Three cases:
- Case I:

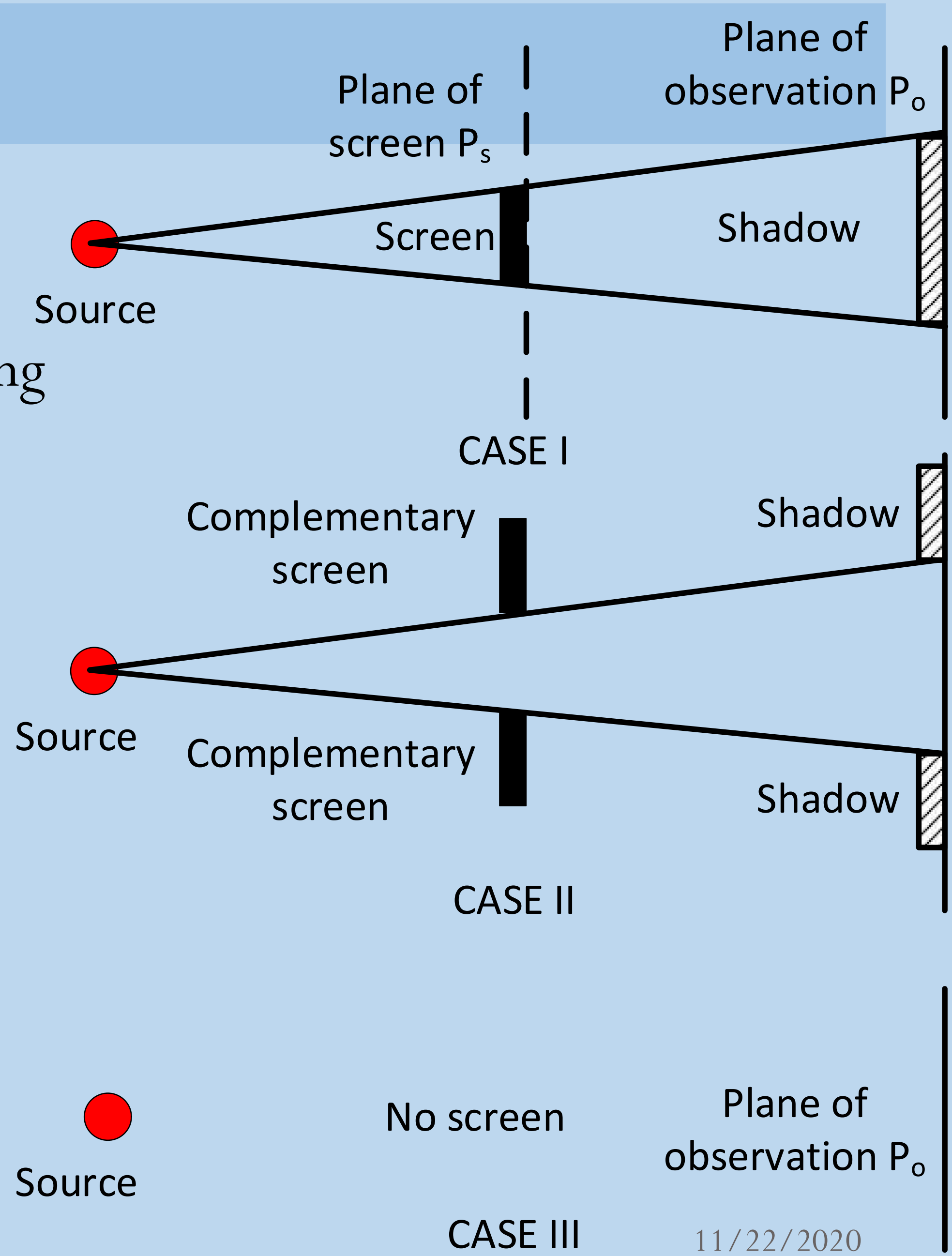
Field at Po: Fs=$f_1(x,y,z)$

- Case II:

Field at Po: Fcs=$f_2(x,y,z)$

- Case III:

Field at Po: Fns=$f_3(x,y,z)$



Slot antennas

- Babinet's principle asserts that the field for the third case without screen
- is equal to the sum of the fields in the first and second cases
  - $f_3(x,y,z)=f_1(x,y,z)+f_2(x,y,z)$
- The Po can be anywhere behind the Ps
- Henry Booker extended this principle in 1946 to antennas
- In antenna analysis,
  - if the screen is PEC
  - then the complementary screen is PMC
- The analysis of Babinet's principle
  - can be done with the help of transmission line analogy

Slot antennas

- Fig. (a) A plane wave of field intensity Ei is incident on an infinite screen of surface admittance admittance Y_1
- (b) A wave of voltage Vi incident

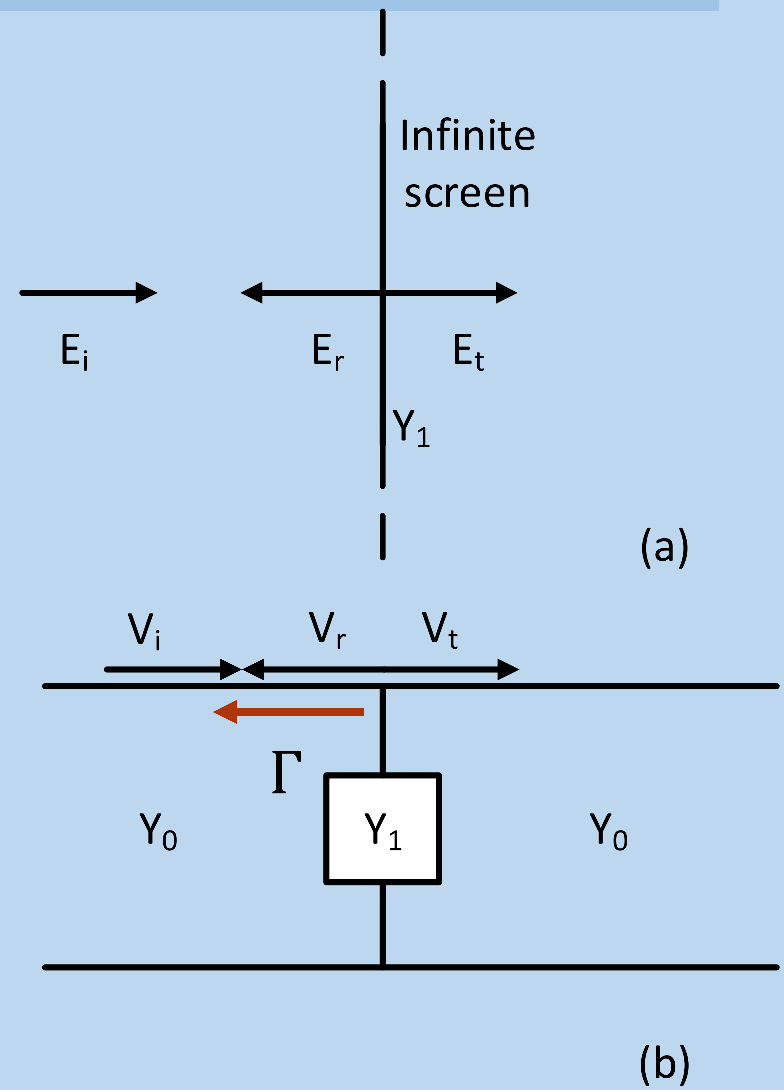
on an infinite transmission line

loaded with a shunt admittance Y_1

placed across the line

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{\frac{1}{Y_L} - \frac{1}{Y_0}}{\frac{1}{Y_L} + \frac{1}{Y_0}} = \frac{Y_0 - Y_L}{Y_L + Y_0}$$

$$\because Y_L = Y_1 + Y_0 \therefore \Gamma = \frac{Y_0 - Y_1 - Y_0}{Y_1 + Y_0 + Y_0} = \frac{-Y_1}{Y_1 + 2Y_0}$$



Slot antennas

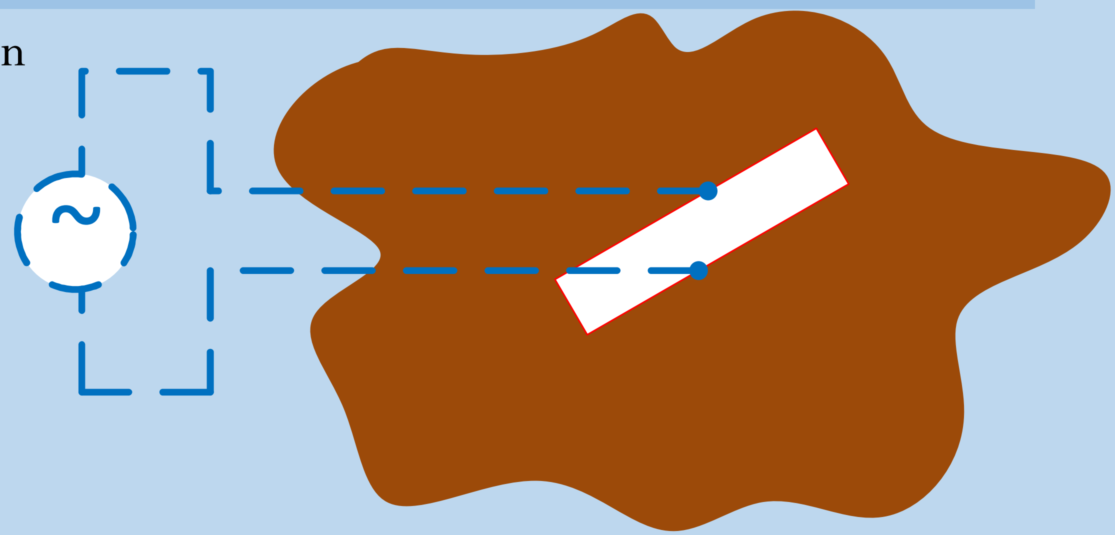
- We can find the transmission coefficient
- $\tau = 1 + \Gamma = 1 + \frac{-Y_1}{Y_1 + 2Y_0} = \frac{Y_1 + 2Y_0 - Y_1}{Y_1 + 2Y_0} = \frac{2Y_0}{Y_1 + 2Y_0}$
- Consider two cases:
- Case I: PEC infinite screen surface admittance admittance Y_1
- Then $\tau_1 = \frac{2Y_0}{Y_1 + 2Y_0}$
- Case II: PMC infinite screen surface admittance admittance Y_2
- Then $\tau_2 = \frac{2Y_0}{Y_2 + 2Y_0}$
- According to Babinet's principle,
- sum of the above two cases would be equal to that the case
- when there are no infinite screen, hence $\tau_1 + \tau_2 = 1$

Slot antennas

- $\tau_1 + \tau_2 = 1$ means that
- $\frac{2Y_0}{Y_1+2Y_0} + \frac{2Y_0}{Y_2+2Y_0} = 1$
- $\Rightarrow 2Y_0(Y_2+2Y_0) + 2Y_0(Y_1+2Y_0) = (Y_2+2Y_0)(Y_1+2Y_0)$
- $\Rightarrow 2Y_0Y_2+8Y_0^2 +2Y_0\,Y_1 = Y_2Y_1 + 2Y_0Y_2 + 2Y_0Y_1 + 4Y_0^2$
- $\Rightarrow 4Y_0^2 = Y_2Y_1$
- which is the *Booker's relation for admittance*
- In terms of impedance,
- $Z_1Z_2 = \frac{Z_0^2}{4} \Rightarrow \sqrt{Z_1Z_2} = \frac{Z_0}{2}$
- The GM of the surface impedances of the screen in two cases considered is equal to ½ the intrinsic impedance of the surrounding medium (e.g. $Z_0 \cong 377\Omega$ for free space)

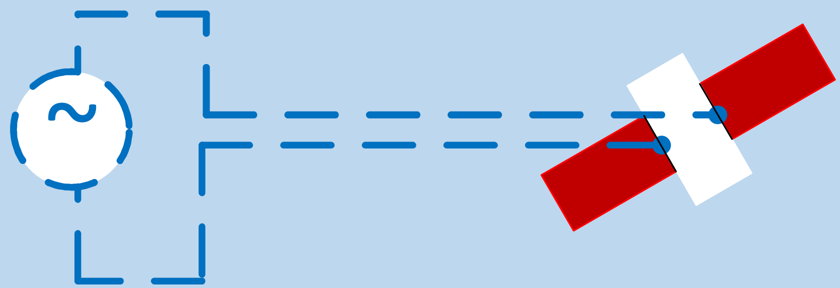
Slot antennas

- Fig. Application of Booker's relation for impedance of slot and dipole antenna



Slot antenna

- $Z_s Z_d = \frac{Z_0^2}{4}$
- Given the dipole antenna impedance Z_d, one can find the impedance of the corresponding slot antenna as
- $Z_s = \frac{35{,}476}{Z_d}$
- Note that in general Z_d is complex number



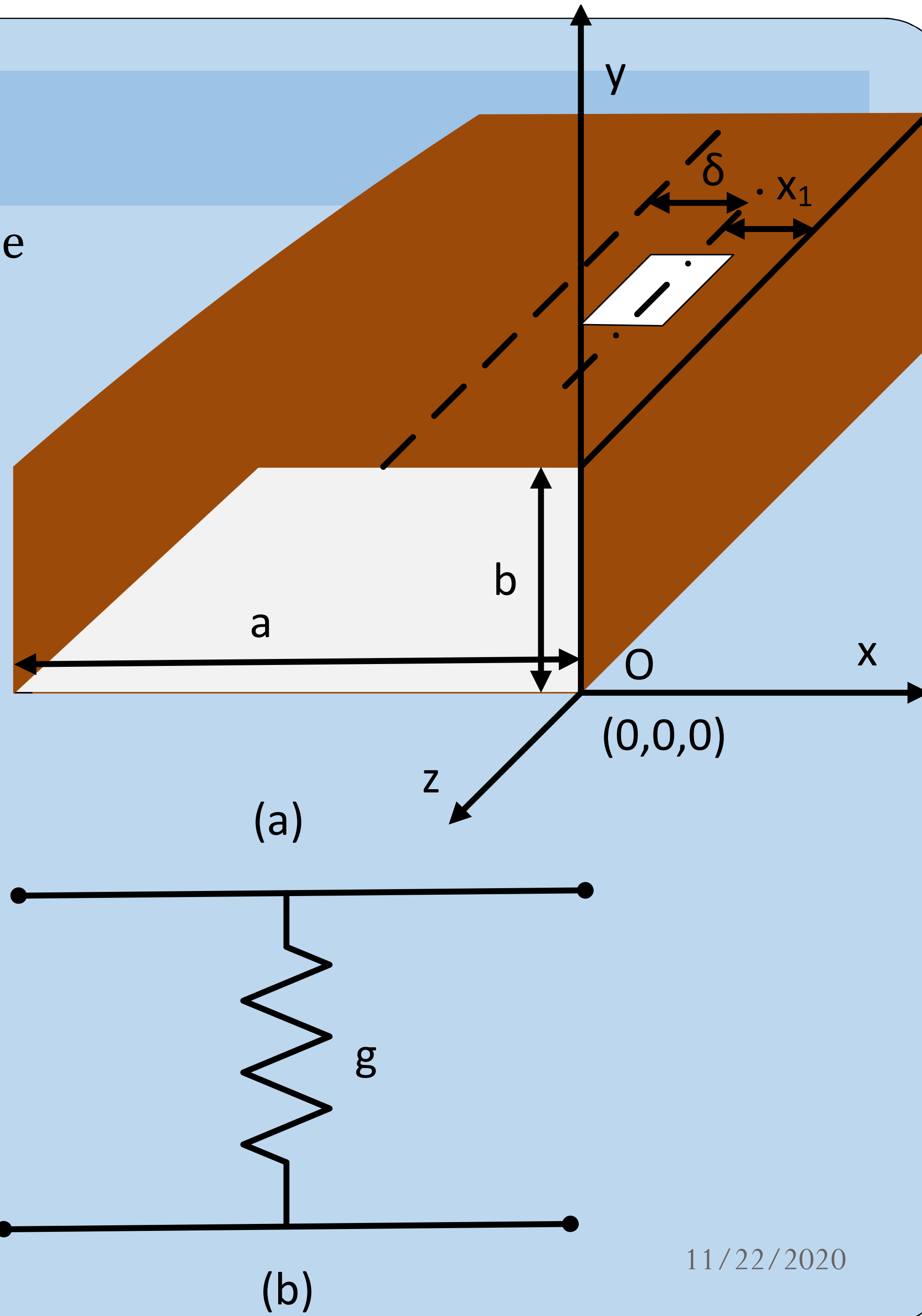
Dipole antenna

Slot antennas

- Half-wavelength dipole ($2L = \frac{\lambda}{2}$) FF radiation pattern (from lecture 18)
- $E_\theta \cong j\eta \frac{I_o e^{-j\beta r}}{2\pi r}\left[\frac{cos(\beta L cos\theta) - co\ \ (\beta L)}{sin\theta}\right] = j\eta \frac{I_o e^{-j\beta r}}{2\pi r}\left[\frac{cos\left(\frac{\pi}{2}cos\theta\right)}{sin\theta}\right]$
- $H_\phi \cong j \frac{I_o e^{-j\beta r}}{2\pi r}\left[\frac{cos\left(\frac{\pi}{2}cos\theta\right)}{sin\theta}\right]$
- Application of Duality principle
- Half-wavelength slot ($2L = \frac{\lambda}{2}$) FF radiation pattern
- $H_\theta \cong j \frac{I_m e^{-j\beta r}}{\eta 2\pi r}\left[\frac{cos\left(\frac{\pi}{2}cos\theta\right)}{sin\theta}\right]$
- $E_\phi \cong -j \frac{I_m e^{-j\beta r}}{2\pi r}\left[\frac{cos\left(\frac{\pi}{2}cos\theta\right)}{sin\theta}\right]$
- Another very popular slot antenna is **slotted waveguide antenna and arrays** also called as travelling wave slot antenna and arrays

Slot antennas

- Fig. (a) Shunt slot in waveguide
- (b) Equivalent circuit
- $g = \frac{Y_s}{Y_0}$
- where g is normalized shunt conductance,
- Y_s is the shunt admittance of the slot in the waveguide and
- Y_0 is the characteristic admittance of the waveguide

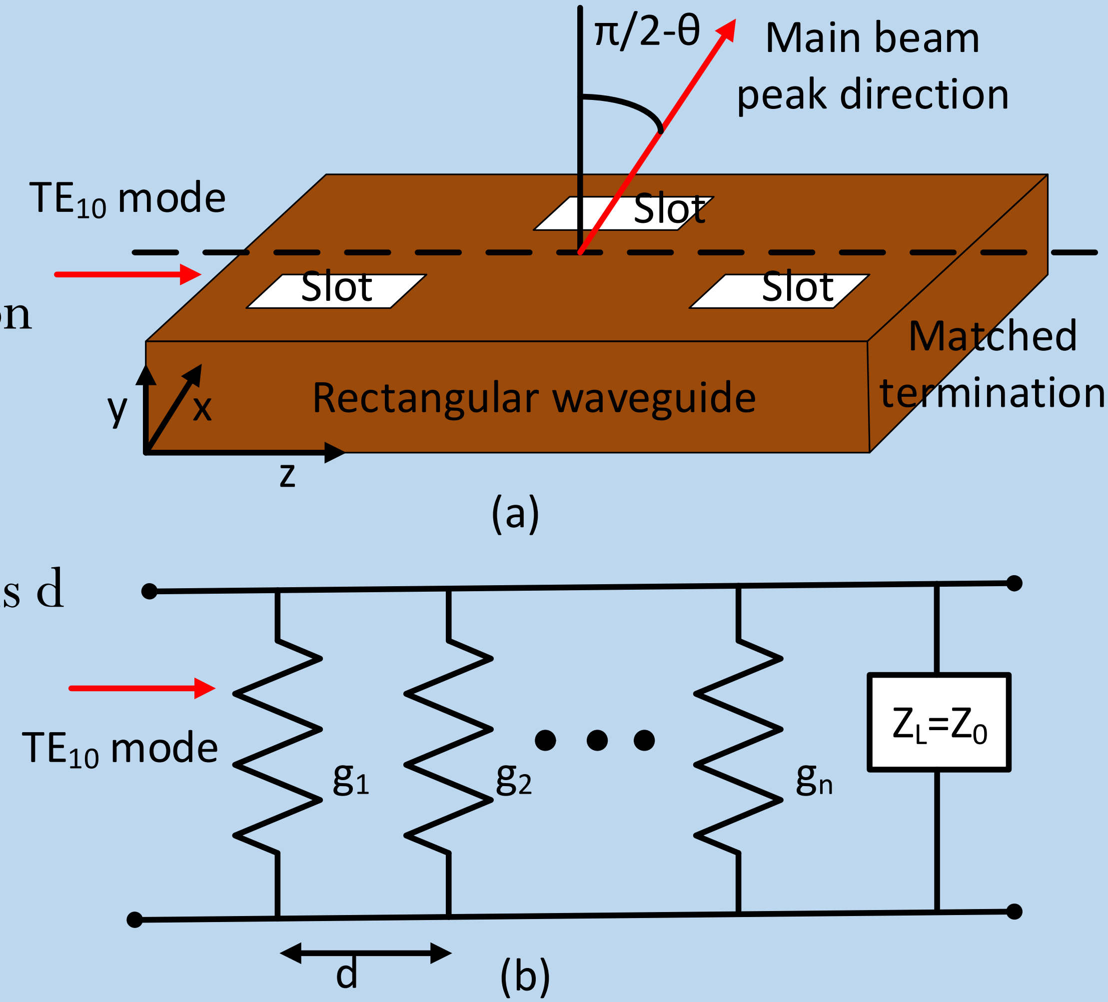


Slot antennas

- $g = 2.09 \frac{\lambda_g}{\lambda_0} \frac{a}{b} cos^2\left(\frac{\pi\lambda_0}{2\lambda_g}\right) sin^2\left(\frac{\pi\delta}{a}\right)$
- where
- λ_g is the guided wavelength of the dominant TE_{10} mode inside the waveguide $\left(\lambda_{g10} = \frac{2\pi}{\beta_{10}} = \frac{2\pi}{\sqrt{\beta^2 - \left(\frac{\pi}{a}\right)^2}} > \lambda_0\right)$
- λ_0 is the free space wavelength
- a and b are the dimension of the waveguide
- $\delta = \frac{a}{2} - x_1$ is the slot offset from the central line
  - which determines the slot conductance
  - with zero at the central line and
  - increase square sinusoidally with δ

Slot antennas

- Fig.
- (a) Slotted waveguide
- antenna array
- (b) Equivalent transmission
- Line model



- Separation between slots is d
- Position vector for any i^th^
- slot centre is given by
- $\vec{r}_i = x_i\hat{x} + b\hat{y} + id\hat{z}$
- where i=1,2,…,n
- and x_i is the off-set distance of the i^{th} slot centre from waveguide side wall

Slot antennas

- Height of the waveguide is common for all slots in the waveguide,
- it has no influence on the radiation pattern of the slotted waveguide antenna array
- It can be neglected and hence $\vec{r}_i = x_i\hat{x} + id\hat{z}$
- AF can be calculated as
- $AF = 1 + a_1 e^{j\psi_1} + a_2 e^{j\psi_2} + \cdots + a_{n-1} e^{j\psi_{n-1}}$
- where a_i is the field excitation amplitude at the i[th] slot
- and $\psi_i = \vec{\beta} \cdot \vec{r}_i - i\beta_{10} d + i\pi$
- $-\beta_{10} d$ is the slot-to-slot phase delay $\left(\beta_{10} = \sqrt{\beta^2 - \left(\frac{\pi}{a}\right)^2}\right)$
- π is phase shift due to the slot staggering (it will disappear if the shunt slots were placed on the same side from the centre line)

Slot antennas

- $\vec{\beta} \cdot \vec{r}_i = (\beta sin\theta cos\phi \hat{x} + \beta sin\theta sin\phi \hat{y} + \beta cos\theta \hat{z}) \cdot (x_i \hat{x} + id\hat{z})$
- $= \beta x_i sin\theta cos\phi + \beta idcos\theta$
- $\psi_i = \beta x_i sin\theta cos\phi + \beta idcos\theta - \beta_{10} d + \pi$
- For radiation pattern in y-z plane, $\phi = \frac{\pi}{2}$
- $\psi_i = \beta idcos\theta - i\beta_{10} d + i\pi$
- AF can be simplified as
- $AF = 1 + a_1 e^{j\psi} + a_2 e^{j2\psi} + \cdots + a_{n-1} e^{j(n-1)\psi}$
- where $\psi = \beta dcos\theta - \beta_{10} d + \pi$
- Main beam is for $\psi = 0$
- Primary lobes: $\psi = \beta dcos\theta - \beta_{10} d + \pi = 2m\pi$
- where m=1,2,..,M

Slot antennas

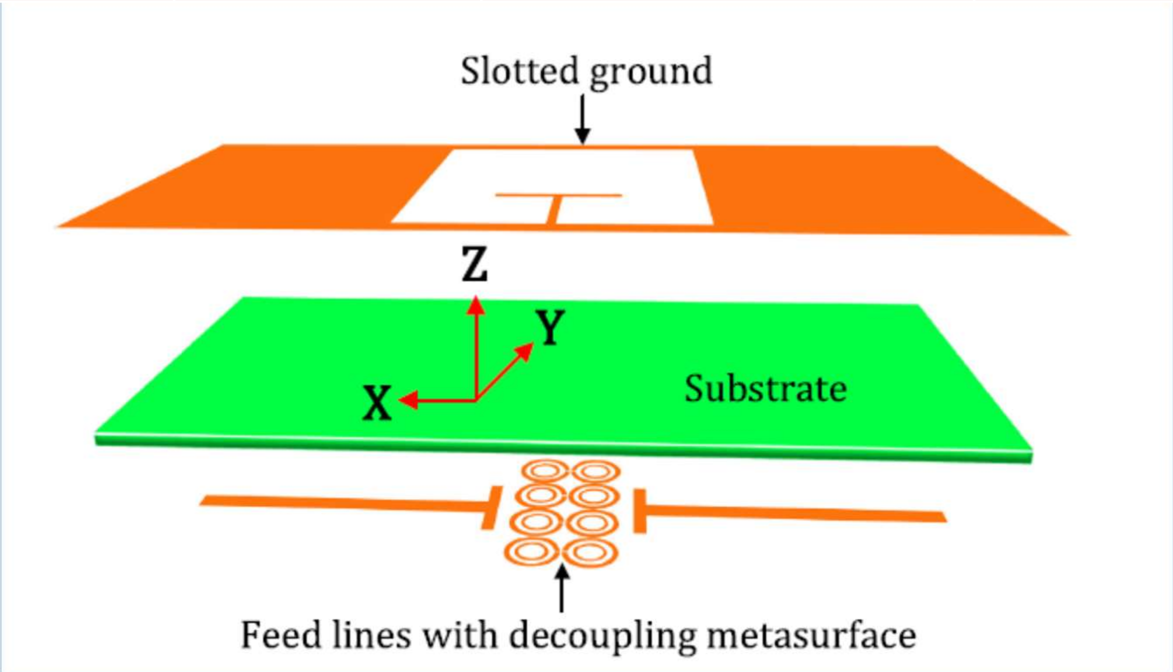
- Hence, primary lobes occur at values of the slot spacing d given by: $\psi = \beta d\cos\theta - \beta_{10} d + \pi = 2m\pi$
- where m=1,2,..,M
- $\frac{2\pi}{\lambda} d\cos\theta - \frac{2\pi}{\lambda_{g10}} d + \pi = 2m\pi$
- $\Rightarrow d\left(\frac{1}{\lambda}\cos\theta - \frac{1}{\lambda_{g10}}\right) = \frac{(2m-1)}{2}$
- $\Rightarrow d\left(\frac{\lambda_{g10}\cos\theta - \lambda}{\lambda\lambda_{g1}}\right) = \frac{(2m-1)}{2}$
- $\Rightarrow d = \frac{(2m-1)}{2}\left(\frac{\lambda\lambda_{g10}}{\lambda_{g10}\cos\theta - \lambda}\right)$
- For $\theta = 0^0, d = \frac{(2m-1)}{2}\left(\frac{\lambda\lambda_{g10}}{\lambda_{g10} - \lambda}\right)$

Slot antennas

- For $\theta = 180^0, d = \frac{(1-2m)}{2}\left(\frac{\lambda\lambda_{g10}}{\lambda_{g10}+\lambda}\right)$
- Infinity occurs at $\lambda_{g10}cos\theta - \lambda = 0$
- $cos\theta = \frac{\lambda}{\lambda_{g10}}$
- ***Some of the slot antenna and arrays from our research group:***
- *All slot antenna and arrays are designed for full-duplex radios*
  - High inter-port isolation Dual circularly polarized (DCP) slot antenna with split ring resonator (SRR) based novel metasurface
  - Series-fed DCP slot antenna array with metallic reflector
  - DCP slot antenna with "8" shaped slots with Interdigital capacitor (IDC)

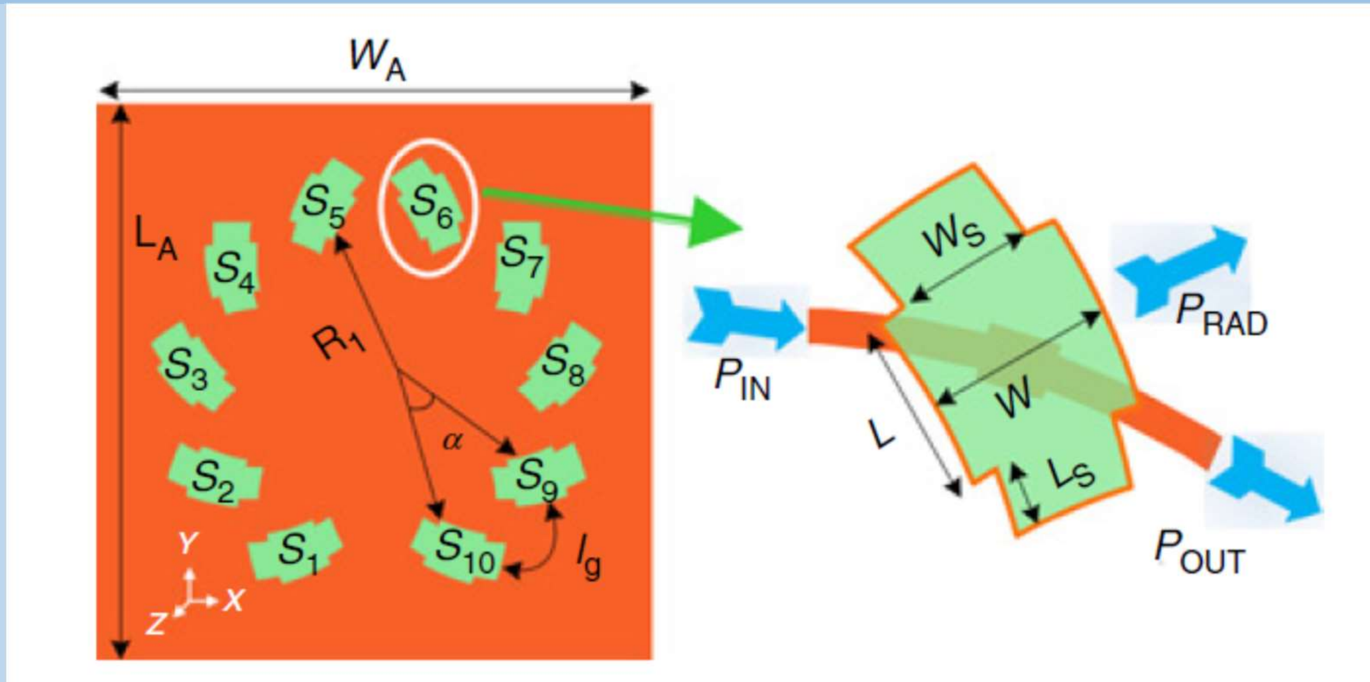
Slot antennas

Isolation (dB)	− 10 dB bandwidth	AR bandwidth	Antenna size	Gain	**Radiation pattern**
27-36	28.52% (f_c=6.45GHz)	8.9% (f_c=6.54 GHz)	$1.58\lambda_0 \times 0.75\lambda_0 \times 0.024\lambda_0$	2.9 to 3.6 dBic	Bidirectional



- Fig. Slot antenna: High inter-port isolation DCP slot antenna with SRR based novel metasurface (Source: https://doi.org/10.1016/j.aeue.2019.05.016)

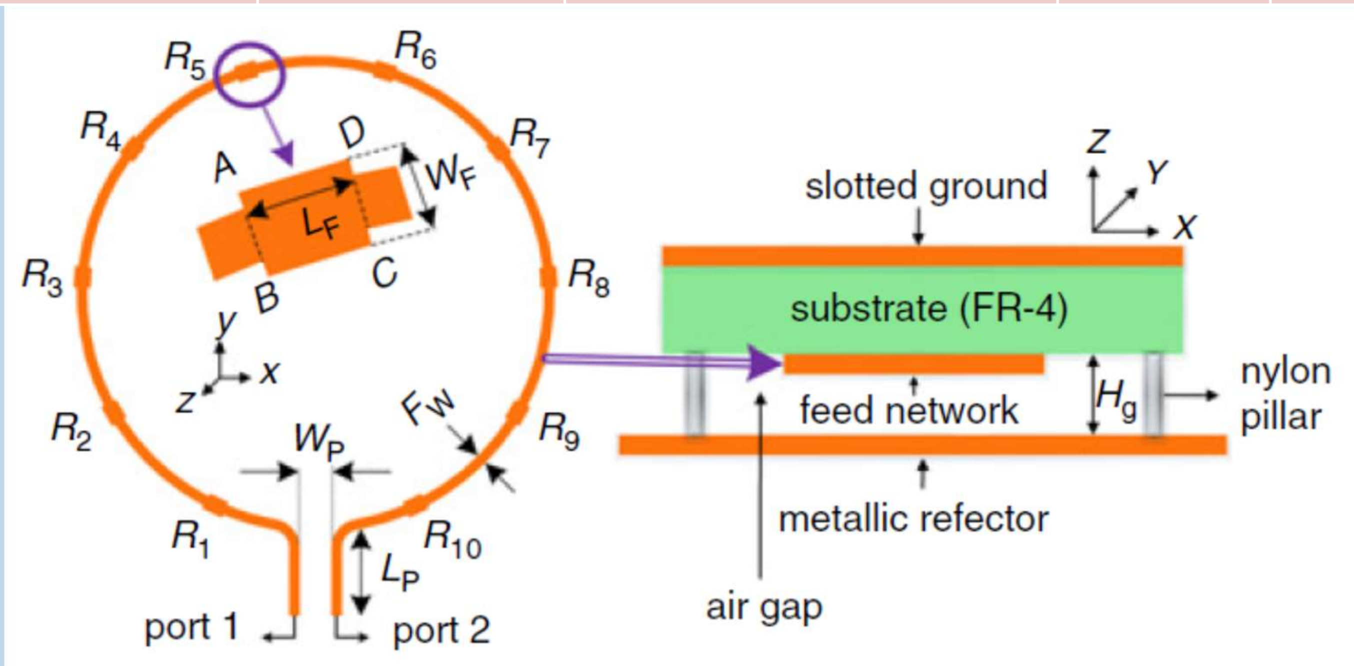
Slot antennas



- Fig. Series-fed DCP slot antenna array: Slotted ground plane with ten slots and radiating single slot model (Source: https://ieeexplore.ieee.org/document/8855215)
- First five slots (S1 to S5 corresponding to Port 1) contribute to 98.7% of the total power radiated by the antenna for γ=0.57

Slot antennas

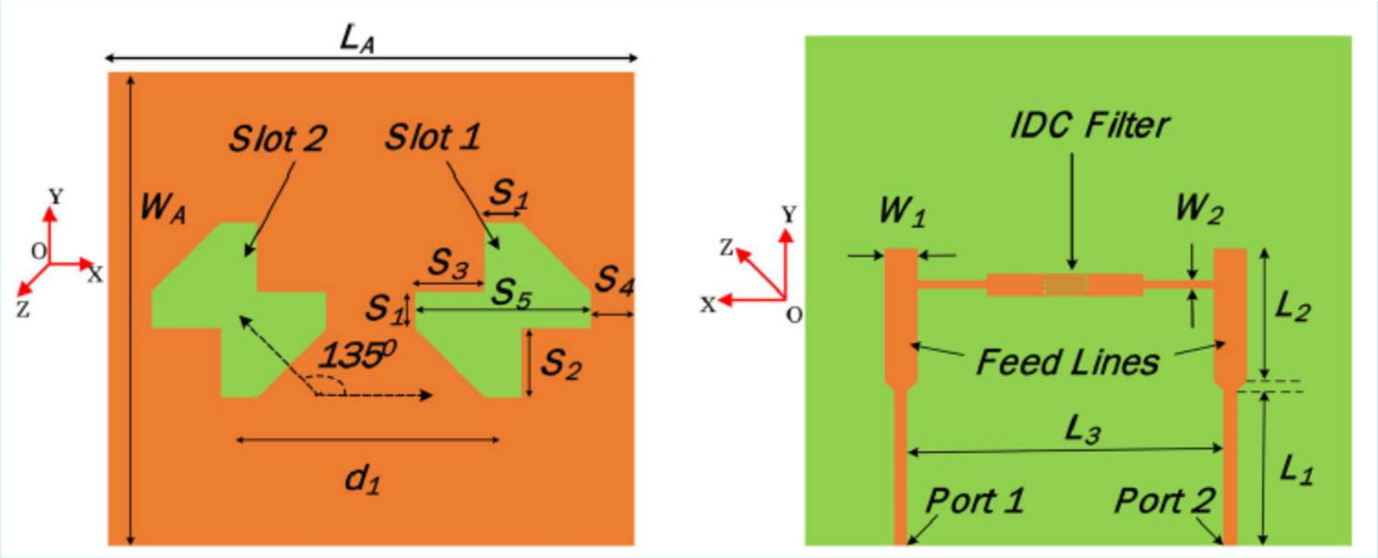
Isolation (dB)	− 10 dB bandwidth	AR bandwidth	Power coupling coefficient	Gain	**Radiation pattern**
25-45	18.46% (f_c=6.45GHz)	13.46% (f_c=6.54 GHz)	$\gamma=1(S21)^{2}=0.57=Pout/Pin$ of an isolated slot	8.2 to 9.5 dBic	Unidirectional



- Fig. Slot antenna array: Series feed network showing the ports and side-view of the antenna showing the metallic reflector (Source: https://ieeexplore.ieee.org/document/8855215)

Slot antennas

Isolation (dB)	− 10 dB bandwidth	AR bandwidth	Antenna size	Gain	**Radiation pattern**
17.6 to 46	15.75% (f_c=2.293GHz)	11.52% (f_c=2.1275 GHz)	$1.14\ \lambda_0 \times 0.91\ \lambda_0$	3 to 5 dBic	Bidirectional



- Fig. DCP slot antenna with “8” shaped slots: front and rear view of the antenna (a) slotted ground (b) feed network with IDC (Source: https://doi.org/10.1002/mmce.21903)