Microwave Engineering 2-6

Chapter 2 Transmission Line

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Learning Objectives

- Learn what the maximum power transmission condition is.
- Understanding real low loss transmission line
- Learn what is different for using lossy transmission instead of lossless transmission line

Learning contents

- Maximum Power Transmission Condition
- Lossy Transmission Lines
- Terminated Lossy Transmission Line

1 Maximum Power Transmission Condition Maximum Power Transn
sless transmission line circuit with arbitra
out impedance looking into terminated tran
 $\lim_{\text{in}} = \frac{V_{\text{in}}}{I_{\text{in}}} = Z_0 \frac{Z_t + jZ_0 \tan \beta l}{Z_0 + jZ_1 \tan \beta l}$
assume general source and load condition
= $R_{$ **iximum Power Transmi**
transmission line circuit with arbitrary
npedance looking into terminated transn
 $\sum_{\substack{i=1 \text{odd } Z_0 + jZ_i \text{ tan } \beta l}} Z_0 + jZ_i \tan \beta l$
me general source and load conditions:
 $j + jX_{\text{in}}$ and $Z_g = R_g + jX_g$ **Maximum Power Transmission Condition**

sysless transmission line circuit with arbitrary generator and load impedances

pput impedance looking into terminated transmission line from generator:
 $Z_m = \frac{V_m}{I_m} = Z_0 \frac{Z_t + jZ_0$ **Taximum Power Transmission Conorsistance**

ess transmission line circuit with arbitrary generator and loat

timpedance looking into terminated transmission line from
 $=\frac{V_{\text{in}}}{I_{\text{in}}} = Z_0 \frac{Z_1 + jZ_0 \tan \beta l}{Z_0 + jZ_1 \tan \beta l$

- Lossless transmission line circuit with arbitrary generator and load impedances
	- Input impedance looking into terminated transmission line from generator:

$$
Z_{\text{in}} = \frac{V_{\text{in}}}{I_{\text{in}}} = Z_0 \frac{Z_l + jZ_0 \tan \beta l}{Z_0 + jZ_l \tan \beta l}
$$

- Let assume general source and load conditions:

Maximum Power Transmission Con-
\nLossless transmission line circuit with arbitrary generator and loa
\nInput impedance looking into terminated transmission line from
\n
$$
Z_{in} = \frac{V_{in}}{I_{in}} = Z_0 \frac{Z_I + jZ_0 \tan \beta I}{Z_0 + jZ_1 \tan \beta I}
$$
\nLet assume general source and load conditions:
\n
$$
Z_{in} = R_{in} + jX_{in} \text{ and } Z_g = R_g + jX_g
$$
\n
$$
P = \frac{1}{2} |V_g|^2 \frac{R_{in}}{(R_{in} + R_g)^2 + (X_{in} + X_g)^2}
$$
\nLet's assume that the generator impedance (Z_g) is only fixed.
\nPower transmission for load matched to transmission line (case s)

- Let's assume that the generator impedance (*Zg*) is only fixed.
- Power transmission for load matched to transmission line (case study 1)

t assume general source and load conditions:
\n₁ =
$$
R_{\text{in}} + jX_{\text{in}}
$$
 and $Z_g = R_g + jX_g$
\n
$$
P = \frac{1}{2} |V_g|^2 \frac{R_{\text{in}}}{(R_{\text{in}} + R_g)^2 + (X_{\text{in}} + X_g)^2}
$$
\nt's assume that the generator impedance (Z_g) is only fixed.
\nweir transmission for load matched to transmission line (case study 1)
\n
$$
P = \frac{1}{2} |V_g|^2 \frac{R_{\text{in}}}{(R_{\text{in}} + R_g)^2 + (X_{\text{in}} + X_g)^2} \Big|_{Z_1 = Z_0 = R_{\text{in}}}
$$
\nweer transmission for generator matched to transmission line (case study 2)
\n
$$
P = \frac{1}{2} |V_g|^2 \frac{R_{\text{in}}}{(R_{\text{in}} + R_g)^2 + (X_{\text{in}} + X_g)^2} \Big|_{Z_1 = Z_0 = R_{\text{in}}}
$$
\n
$$
= \frac{1}{2} |V_g|^2 \frac{R_g}{R_g^2 + X_g^2}
$$

- Power transmission for generator matched to transmission line (case study 2)

$$
P = \frac{1}{2} |V_g|^2 \frac{R_{\text{in}}}{(R_{\text{in}} + R_g)^2 + (X_{\text{in}} + X_g)^2} \bigg|_{Z_g = Z_{\text{in}}} = \frac{1}{8} |V_g|^2 \frac{R_g}{R_g^2 + X_g^2}
$$

3

- Power transmission for generator matched to transmission line (case study 3)

1 **Maximum Power Transmission Condition**
\nPower transmission for generator matched to transmission line (case study 3)
\n
$$
P = \frac{1}{2} |V_g|^2 \frac{R_n}{(R_n + R_g)^2 + (X_m + X_g)^2} \Big|_{R_n = R_g} = \frac{1}{2} |V_g|^2 \frac{1}{4R_g}
$$
\n- Maximum power condition: case study 3
\n
$$
Z_m = Z_g^*
$$
\n
$$
Z_m = Z_g^*
$$
\n
$$
Y_g \underbrace{\left\{\frac{Z_g}{Z_g}\right\}}_{Z_{4m} \underbrace{\frac{1}{Z_g}}_{Z_{4m} \
$$

$$
P = \frac{1}{2} |V_g|^2 \frac{R_{\text{in}}}{(R_{\text{in}} + R_g)^2 + (X_{\text{in}} + X_g)^2} \bigg|_{Z_g = Z_{\text{in}}} = \frac{1}{2} |V_g|^2 \frac{R_g}{4(R_g^2 + X_g^2)}
$$
 (case study 2)

4

1 Maximum Power Transmission Condition

§ **Maximum power transfer condition for DC related circuit** in condition of fixed source resistance

Maximum Power Transmission Condition
\n**Maximum power transfer condition for DC related circuit in condition of fixed source resistance**
\n
$$
V_L = V_s \frac{R_L}{R_s + R_L}, \qquad I_L = \frac{V_s}{R_s + R_L}
$$
\n
$$
P_L = I_L V_L = V_s^2 \frac{R_L}{(R_s + R_L)^2}
$$
\n
$$
P_{L, \text{max}} = \frac{dP_L}{dR_L} = V_s^2 \frac{(R_s + R_L)^2 - 2R_L (R_s + R_L)}{(R_s + R_L)^4} = V_s^2 \frac{R_s^2 - R_L^2}{(R_s + R_L)^4} = 0 \Leftrightarrow R_s = R_L
$$
\n
$$
\Rightarrow \text{ The condition for the maximum DC power transferring to load is for same source and load resistances.}
$$
\n**Maximum power transfer condition for AC or microwave circuit**
\n
$$
Z_L = Z_s^* \text{ or } Z_s = Z_L^*
$$
\n
$$
\Rightarrow Z_L = R_L + jX_L = R_s - jX_s^*
$$
\n
$$
\Rightarrow Z_L = R_L + jX_L = R_s - jX_s^*
$$
\n
$$
\Rightarrow \text{The maximum microwave power transfer condition is} \qquad V_s \qquad V_L
$$
\n
$$
\Rightarrow \text{where with the maximum DC power transfer condition}
$$
\n**Example 2.1**
\n**Example 3.1**
\n**Example 4.1**
\n**Example 4**

- è The condition for **the maximum DC power transferring** to load is for *same source and load resistances*.
- § **Maximum power transfer condition for AC or microwave circuit**

*

è The **maximum microwave power transfer** condition is same with the maximum DC power transfer condition **except resonance condition**.

è *Frequency selective maximum power delivery condition*

1.1 Lossy Transmission Lines 2

- Effects of loss on transmission line behavior
- How many the attenuation constant can be calculated?
	- General complex propagation constant:

Lossy Transmission Lines
\neffects of loss on transmission line behavior
\nHow many the attenuation constant can be calculated?
\nGeneral complex propagation constant:
\n
$$
\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}
$$
\n
$$
= \sqrt{(j\omega L)(j\omega C)(1 + \frac{R}{j\omega L})(1 + \frac{G}{j\omega C})} = j\omega \sqrt{LC} \sqrt{1 - j(\frac{R}{\omega L} + \frac{G}{\omega C})} - \frac{RG}{\omega^2 LC}
$$
\n
$$
\beta = j\omega \sqrt{LC} \sqrt{1 - \frac{RG}{\omega^2 LC}}
$$
\n
$$
\beta
$$
\nis not a linear function of frequency (e.g., $\beta \neq a\omega$).
\n
$$
\Rightarrow
$$
 Phase velocity ($v_p = \omega / \beta$) will be different for different frequencies ω .

- β is not a linear function of frequency (e.g., $\beta \neq a\omega$).
	- \rightarrow Phase velocity ($v_p = \omega / \beta$) will be different for different frequencies ω .
	- \rightarrow The various frequency components of a wideband signal will travel with different phase velocities.
	- \rightarrow The arrival at the receiver end of the transmission line is at slightly different times. \rightarrow **Dispersion** (: a distortion of the signal)
	- \rightarrow Undesirable effect

Lossy Transmission Lines $\overline{2}$

- For low-loss transmission line ($R \ll \omega L$, $G \ll \omega C$) (\leftrightarrow low conductor loss and low dielectric loss),

$$
\gamma \approx j\omega\sqrt{LC}\sqrt{1-j(\frac{R}{\omega L}+\frac{G}{\omega C})} \quad \leftarrow RG \ll \omega^2 LC
$$

By using $\sqrt{1+x} \approx 1+x/2+\cdots$,

$$
\gamma = \alpha + j\beta \approx j\omega\sqrt{LC}\left[1-\frac{j}{2}\left(\frac{R}{\omega L}+\frac{G}{\omega C}\right)\right]
$$

$$
\alpha \approx \frac{1}{2}(R\sqrt{\frac{C}{L}}+G\sqrt{\frac{L}{C}})=\frac{1}{2}(\frac{R}{Z_0}+GZ_0), \quad \beta = \omega\sqrt{LC}
$$

 $\rightarrow \beta$ of low loss transmission line is almost similar to lossless transmission line.

where $Z_0 = (L/C)^{0.5}$: characteristic impedance of lossless transmission line α : attenuation constant

 β : phase constant

Terminated Lossy Transmission Line 3 ated Lossy Transmissic
sion line terminated in a load impedance
agation constant : $\gamma = \alpha + j\beta$
ow loss transmission line $(Z_0 \approx \sqrt{\frac{L}{C}})$
urrent waves on low loss transmission l **inated Lossy Transn**
mission line terminated in a load in
ropagation constant : $\gamma = \alpha + j\beta$
n: low loss transmission line $(Z_0 \approx A)$
d current waves on low loss transm
 $+ [e^{-\gamma z} + \Gamma e^{\gamma z}]$
 $-[e^{-\gamma z} - \Gamma e^{\gamma z}]$ **Transmission Line**
 CONSY Transmission Line
 CONSY Transmission Line
 CONSY Transmission Line
 Z_L
 $= \exp(\frac{Z_L}{C})$
 \Rightarrow and current waves on low loss transmission line
 $= V_0^+[e^{-\gamma z} + \Gamma e^{\gamma z}]$
 $= \frac{V_0^+[e^{-\gamma z} - \Gamma$ **rminated Lossy Transmission Line**

ransmission line terminated in a load impedance Z_L

ex propagation constant : $\gamma = \alpha + j\beta$

ption: low loss transmission line $(Z_0 \propto \sqrt{\frac{L}{C}})$

e and current waves on low loss transm

- Lossy transmission line terminated in a load impedance Z_L
	- Complex propagation constant : $\gamma = \alpha + j\beta$
	-
	- Assumption: low loss transmission line $(Z_0 \approx \sqrt{\frac{L}{C}})$
- Voltage and current waves on low loss transmission line

$$
V(z) = V_0^+[e^{-\gamma z} + \Gamma e^{\gamma z}]
$$

$$
I(z) = \frac{V_0^+}{Z_0} [e^{-\gamma z} - \Gamma e^{\gamma z}]
$$

where Γ : reflection coefficient at load (= $(Z_L - Z_0) / (Z_L + Z_0)$), sion line terminated in a load impedan
agation constant : $\gamma = \alpha + j\beta$
ow loss transmission line $(Z_0 \approx \sqrt{\frac{L}{C}})$
irrent waves on low loss transmission
 $Z^z + \Gamma e^{yz}$]
 $Z^z - \Gamma e^{yz}$]
eflection coefficient at load (= (Z_L -

 V_0^+ : incident voltage amplitude referenced at $z = -l$

- Reflection coefficient at a distance *l* from load:

 $\Gamma(-l) = \Gamma e^{-2j\beta l} e^{-2\alpha l} = \Gamma e^{-2\gamma l}$

- Input impedance Z_{in} at a distance *l* from load:

$$
Z_{\text{in}} = \frac{V(-l)}{I(-l)} = Z_0 \frac{Z_L + Z_0 \tanh \gamma l}{Z_0 + Z_L \tanh \gamma l}
$$

Terminated Lossy Transmission Line 3

- Power delivered to input of terminated line at *z* = -*l*:

Terminated Lossy Transmission Line
\nPower delivered to input of terminated line at
$$
z = -l
$$
:
\n
$$
P_m = \frac{1}{2} \text{Re}\left[V(-l)l^*(-l)\right] = \frac{|V_0^*|^2}{2Z_0} \text{Re}\left[e^{i\theta} + \text{Re}^{-i\theta}(e^{i\theta}) - \text{Im}^{-i}e^{-i\theta}\right] \left(-\gamma - \alpha + j\beta\right)
$$
\n
$$
= \frac{|V_0^*|^2}{2Z_0} \text{Re}\left[e^{i\theta e^{i\beta t} + \text{Re}^{-i\theta}e^{-j\beta t}\right) \left(e^{i\theta}e^{-j\beta t} - \text{Im}^{-i}e^{-i\theta}e^{i\beta t}\right]
$$
\n
$$
= \frac{|V_0^*|^2}{2Z_0} \text{Re}\left[e^{i\alpha t} - \text{Im}^{-i}e^{-i\alpha t}e^{-j\beta t} - \text{Im}^{-i}e^{-i\alpha t}\right]
$$
\n
$$
= \frac{|V_0^*|^2}{2Z_0} \text{Re}\left[e^{2\alpha t} - \text{Im}^{-i}e^{-2\alpha t}\right] \left(-\text{Im}^{-i}e^{-i\beta t}\right)
$$
\n
$$
= \frac{|V_0^*|^2}{2Z_0} \text{Im}^{-i}e^{-2\alpha t} - \text{Im}^{-i}e^{-2\alpha t}\right] \left(-\text{Im}^{-i}e^{-i\beta t}\right)
$$
\n
$$
= \frac{|V_0^*|^2}{2Z_0} \text{Im}^{-1}e^{-2\alpha t} - \text{Im}^{-1}e^{-2\alpha t}\right] \left(-\text{Im}^{-1}e^{-2\alpha t}\right)
$$
\n
$$
= \frac{|V_0^*|^2}{2Z_0} \text{Im}^{-1}e^{-2\alpha t} - \text{Im}^{-1}e^{-2\alpha t}\right]
$$
\n
$$
= \frac{|V_0^*|^2}{2Z_0} \text{Im}^{-1}e^{-2\alpha t} - \text{Im}^{-1}e^{-2\alpha t}\text{Im}^{-1}e^{-2\alpha t}\text{Im}^{-1}e^{-2\alpha t}\text{Im}^{-1}e^{-2\alpha t}\text{Im}^{-1}e^{-2\alpha t}\text{Im}^{-1}e^{-2\alpha t}\text{Im}^{-1}e^{-2\
$$

- § Impedance matching
- $Z_{\text{in}} = Z_{\text{g}}^{*}$ or $Z_{\text{g}} = Z_{\text{in}}^{*}$ view
 \sum_{g}^{*} or $Z_{g} = Z_{in}^{*}$
 $Z_{in} = R_{in} + jX_{in} = R_{g} - jX_{g}^{*}$ Review

bedance matching
 $\sum_{\text{in}} = Z_g^*$ or $Z_g = Z_{\text{in}}^*$
 $\Leftrightarrow Z_{\text{in}} = R_{\text{in}} + jX_{\text{in}} = R_g - jX_g^*$ **eW**

matching

or $Z_g = Z_{in}^*$
 $\frac{1}{\sin x} = R_{in} + jX_{in} = R_g - jX_g^*$

erence plane **iew**

ce matching
 \int_{g}^{*} or $Z_{g} = Z_{in}^{*}$
 $Z_{in} = R_{in} + jX_{in} = R_{g} - jX_{g}^{*}$

geforence plane $\frac{1}{g} - jX_g^*$ **Review**
 $Z_{\text{in}} = Z_{\text{s}}^*$ or $Z_{\text{s}} = Z_{\text{in}}^*$
 $\Leftrightarrow Z_{\text{in}} = R_{\text{in}} + jX_{\text{in}} = R_{\text{s}} - jX_{\text{s}}^*$

At any reference plane **iew**

e matching

or $Z_g = Z_m^*$
 $Z_m = R_m + jX_m = R_g - jX_g^*$

eference plane

transmission line **Leview**

dance matching
 $= Z_g^*$ or $Z_g = Z_m^*$
 $\Leftrightarrow Z_m = R_m + jX_m = R_g - jX_g^*$

my reference plane

oss transmission line
	- At any reference plane
-
- Low loss transmission line
- It is important to understand why smallest transmission line is used.

*

- Signal loss and distortion
- Incident and reflected wave power loss

Chapter Review Chapter Review

Transmission line (TRL): carrier to transmit electric energy, signals, data, and information from one point to another point with small insertion loss ate)
 $\omega L = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \neq R_0$

§ Analyzing approaches

1) Maxwell's equations: electromagnetic field method (complete & accurate) 2) Circuit equations: equivalent voltage and current analysis method (intuitive & inaccurate) rate)
itive & inaccurate)
ics \rightarrow SRF
 $\frac{\partial f}{\partial t} = -\frac{V_o}{I_o} = \frac{R + j\omega L}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \neq R_0$ $\frac{\text{cm(s)}}{\text{cot(s)}}$
 accurate)
 1 (intuitive & inaccurate)
 2₀ = $\frac{V_o^+}{I_o^+} = -\frac{V_o^-}{I_o^-} = \frac{R + j\omega L}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \neq R_0$
 (*ω***)**
 11 Trate)
 I I discussed in accurate)
 I $\frac{V_0^+}{I_0^+} = -\frac{V_0^-}{I_0^-} = \frac{R + j\omega L}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \neq R_0$
 I 1 Trate)
 $\frac{jaL}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \neq R_0$ ate)

tive & inaccurate)
 $\cos \rightarrow \text{SRF}$
 $\frac{d\vec{r}}{dt} = -\frac{V_o^+}{I_o^-} = \frac{R + j\omega L}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \neq R_0$ ate)

itive & inaccurate)

ics \rightarrow SRF
 $\frac{v}{f_o^+} = -\frac{V_o^-}{I_o^-} = \frac{R + j\omega L}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \neq R_0$ = = - =

- General lumped elements $(R, L, C, \text{etc.})$ frequency dependent characteristics \rightarrow SRF
- Characteristic impedance: a ratio of voltage wave to current wave $Z_0 = \frac{V_0}{I_0^+} = -\frac{V_0}{I_0^-} = \frac{K + J \omega L}{K} = \sqrt{\frac{K + J \omega L}{C + j \omega C}} \neq R_0$ $+ j\omega L \qquad |R + j\omega L \rangle$ $=\frac{R+\sqrt{\omega L}}{2}=\sqrt{\frac{R+\sqrt{\omega L}}{2}+R_0}$
- Complex propagation constant: $\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} = f(\omega)$

 $+ j\omega C$

 $+ j \omega L$

R

 $\neq R_0$

Chapter Review Chapter Review

Voltage reflection coefficient (Γ) = Reflected voltage wave amplitude / Incident voltage wave amplitude **hapter Review**

e reflection coefficient (Γ) = Reflected voltage wave amplitude / Incident
 $\frac{V_0^-}{V_0^+} = \frac{|V_0^-|e^{i\theta^+}}{|V_0^+|e^{i\theta^+}|} = \frac{Z_L - Z_0}{Z_L + Z_0} = |\Gamma|e^{i\theta}$

= **0**, **no reflected wave.** $\rightarrow Z_L = Z_0$ ((Imped **Chapter Review**

tage reflection coefficient (Γ) = Reflected voltage wave amplitude / Incident volta
 $\Gamma = \frac{V_0^-}{V_0^+} = \frac{|V_0^-|e^{i\phi^+}}{|V_0^+|e^{i\phi^+}|} = \frac{Z_L - Z_0}{Z_L + Z_0} = |\Gamma|e^{i\theta}$
 $\Gamma = 0$, no reflected wave. $\rightarrow Z_L$

Chapter Review
\ntage reflection coefficient (Γ) = Reflected voltage wave
\n
$$
\Gamma = \frac{V_0^-}{V_0^+} = \frac{|V_0^-|e^{j\phi^-}}{|V_0^+|e^{j\phi^+}|} = \frac{Z_L - Z_0}{Z_L + Z_0} = |\Gamma|e^{j\theta}
$$
\n
$$
\Gamma = 0, \text{ no reflected wave.} \implies Z_L = Z_0 \text{ (Impedance)}
$$
\n
$$
V = 1 + |\Gamma|
$$

- **•** If $\Gamma = 0$, no reflected wave. $\rightarrow Z_L = Z_0$ ((Impedance) Matching!!)
- (Voltage) Standing wave ratio (VSWR): SWR = $\frac{v_{\text{max}}}{V} = \frac{1+|V|}{1+|V|}$ **hapter Review**
 *v*₆ $\frac{V_0^-}{V_0^+} = \frac{|V_0^-|e^{i\theta}}{|V_0^+|e^{i\theta^+}|} = \frac{Z_L - Z_0}{Z_L + Z_0} = |\Gamma|e^{i\theta}$
 *V*₆ *v*₆ $\frac{V_0^-}{V_0^+|e^{i\theta^+}|} = \frac{Z_L - Z_0}{Z_L + Z_0} = |\Gamma|e^{i\theta}$
 9. no reflected wave. $\rightarrow Z_L = Z_0$ ((Impedance) M min $\begin{array}{c|c} \hline \end{array}$ $\begin{array}{c} \hline \end{array}$ $1 + |\Gamma|$ $\text{SWR} = \frac{7 \text{ max}}{15} = \frac{14}{15}$ $1-|\Gamma|$ V_{max} 1+| Γ | V_{\min} 1- $|\Gamma|$

- Two successive voltage maxima (or minima) on TRL: $l = \lambda / 2$
- **•** Input impedance seen looking toward the load at $z = -l: Z_{\text{in}}$ 0 and $p\ell$ $\Gamma = 0$, **no reflected wave.** $\rightarrow Z_L$ =
ltage) Standing wave ratio (VSWR):

b successive voltage maxima (or min

ut impedance seen looking toward th
 $\Gamma_{\text{in}} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l}$ $V_g \bigoplus$ $0 \perp J$ \sim L tan μ $\tan \beta l$ $\frac{|z_g|}{|z_g|}$ $\tan \beta l$ $z_{\text{in}} \Leftrightarrow$ L^{-1} J^2 ₀ can μ ¹ L and μ **Chapter Review**

Utage reflection coefficient (Γ) = Reflected voltage wave amplitude / Incide
 $\Gamma = \frac{V_0^-}{V_0^+} = \frac{|V_0^-|e^{i\theta}}{|V_0^+|e^{i\theta^+}} = \frac{Z_L - Z_0}{Z_L + Z_0} = |\Gamma|e^{i\theta}$
 $\Gamma = 0$, no reflected wave. $\rightarrow Z_L = Z_0$ ((Im **Filection coefficient (** Γ **)** = Reflected voltage wave amplitude / Incide
 $= \frac{|V_0^-|e^{i\phi^-}}{|V_0^+|e^{i\phi^+}} = \frac{Z_L - Z_0}{Z_L + Z_0} = |\Gamma|e^{i\theta}$
 no reflected wave. $\rightarrow Z_L = Z_0$ ((Impedance) Matching!!)

Standing wave ratio (VSW βl $\frac{Z_g}{4}$ $\frac{Q_{\text{max}}}{4}$ βl $\qquad V_s \leftrightarrow Z_{\text{in}} \Rightarrow Z_0, \beta$ $V_L |Z_L|$ + jZ_0 tan βl $=Z_0 \frac{Z_L + J Z_0 \tan \rho t}{Z_L + Z_0 \tan \rho t}$ $+ jZ_L \tan \beta l$'s φ $V_g(\mathcal{L})$ *z -l* $Z_{\text{g}} \longleftarrow$ *+ - +* $\overrightarrow{V}_{\text{in}}$ Z_0 , β V_L $\overrightarrow{Z_L}$ I_{in} \leftarrow V_L Z_L *IL*
- TRL terminated with short or open circuit can be used inductor or capacitor in microwave frequency range.
	- Frequency and transmission line length dependent
	- Periodic characteristics

Chapter Review

TRL of characteristic impedance Z_0 connected different characteristic impedance (Z_1) transmission line \blacksquare

 $\overbrace{\text{min}\text{ and }\text{ }}^{T}\text{ }$

 $Z₁$

 $JMD -$

- Reflection coefficient: $\Gamma = \frac{Z_1 Z_0}{Z_1 + Z_0}$
- Reflection and transmission
- Smith chart \blacksquare
	- Reflection coefficient plane
	- Analyzing approaches for visualizing transmission line phenomenon
	- Intuition about transmission line and impedance-matching problems
- **Slotted TRL** \blacksquare
	- Waveguide, coaxial cable
	- Measurement issues: (V)SWR, distance of (first) voltage maximum (or minimum) from load, Z_L , λ , etc.
	- In real condition, network analyzer is used generally.
- Maximum power transmission condition: impedance conjugate matching $7 - 7$

$$
\sum_{\text{in}} \frac{Z_{\text{in}} - Z_g}{\text{Lossy TRL:}} \quad P_{\text{loss}} = P_{\text{in}} - P_L = \frac{|V_0^+|^2}{2Z_0} \Big[(e^{2\alpha l} - 1) + |\Gamma|^2 (1 - e^{-2\alpha l}) \Big]
$$

